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DIRECT VISUAL AND RADAR METHODS FOR THE DETECTION, QUANTIFICATI--ETC(U)
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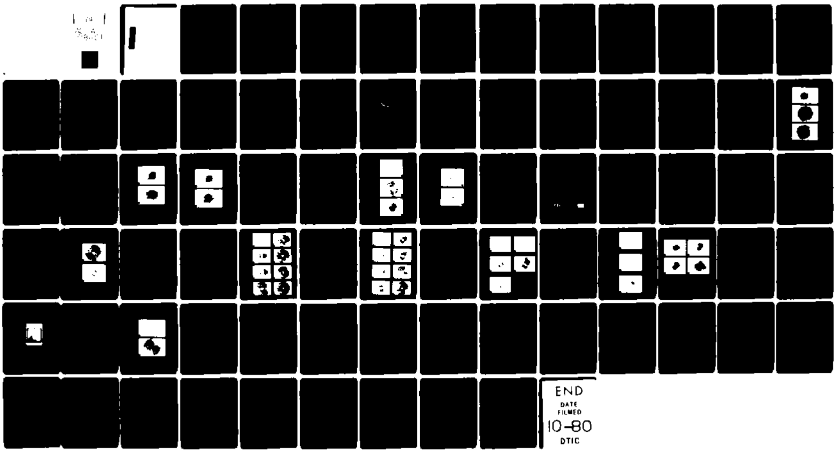

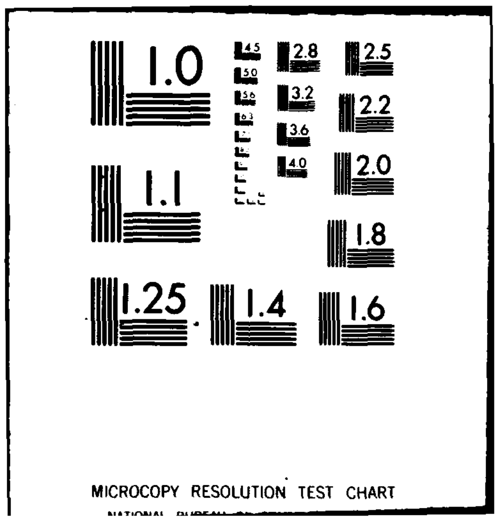
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ABSTRACT

The seasonal migrations of birds are not only of significant interest to ornithologists but they have demanded attention from aviation interests as well. The problem of bird/aircraft collisions has received increased attention during the last decade. Annual costs associated with such collisions have been as high as 45 million dollars for U. S. Air Force operations alone. Since 1969 direct visual and radar studies have been conducted in the southeastern United States to detect, quantify, monitor, and predict the huge seasonal migrations of birds in an effort to reduce the hazards that migrating birds pose to aviation. These studies have concentrated on the development of techniques that provide radar operators with information on the type and quantity of birds aloft as well as on the height and direction of the movements.

Two types of radars have been used in the studies, the WSR-57 operated by the National Weather Service and the ASR-4 operated by the Federal Aviation Administration. The details and operational performance of both types of radar are discussed. The use of ~~these~~ radar~~s~~ to detect, quantify, and monitor the movements of birds aloft is treated in detail. Direct visual means of studying migration are also included because these techniques aid in identifying the birds responsible for the echoes displayed on the radar screens, and they are indispensible to quantifying the radar displays of migrating birds. A new image intensifier--ceilometer technique for viewing migrating birds at night is described. The technique can be automated and permits remote monitoring by means of closed circuit television. Forecasting dense migrations of birds in spring and fall has great utility to the aviation community, and this topic is covered in some detail. The combined methods of direct visual observation and radar surveillance in conjunction with knowledge of the weather conditions that are conducive to dense movements of birds offer great promise for reducing the hazards that migrating birds pose to aircraft. The methods are also essential for basic investigations of the seasonal movements of millions of birds through the atmosphere.

DIRECT VISUAL AND RADAR METHODS
FOR THE
DETECTION, QUANTIFICATION, AND PREDICTION
OF
BIRD MIGRATION

by

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30 April 1980

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The seasonal migrations of birds are not only of significant interest to ornithologists but they have demanded attention from aviation interests as well. The problem of bird/aircraft collisions has received increased attention during the last decade. Annual costs associated with such collisions have been as high as 45 million dollars for U. S. Air Force operations alone. Since 1969 direct visual and radar studies have been conducted in the southeastern United States to detect, quantify, monitor, and predict the huge seasonal migrations of birds in an effort to reduce the hazards that migrating birds pose to aviation. These studies have concentrated on the development of techniques that provide radar operators with information on the type and quantity of birds aloft as well as on the height and direction of the movements.

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PREFACE AND ACKNOWLEDGMENTS

This work presents an overview of the research I have conducted over the last 10 years on the detection, quantification, and monitoring of bird migration during the day and at night. The treatment is sufficiently detailed so that radar technicians, flight controllers, and ornithologists may use the methods in their own work. This information hopefully will prove useful in reducing the hazards that migrating birds pose to aircraft, and the techniques discussed will be helpful to students of bird migration in their investigatioons of migrating birds aloft.

The work included was sponsored by the Air Force Office of Scientific Research (AFOSR) through grants from September 1969 through February 1980. The research would not have been possible without the great assistance provided by the personnel of the United States National Weather Service of the National Oceanic and Atmospheric Administration (NWS) and the Federal Aviation Administration (FAA). Both of these agencies permitted use of the radar equipment so necessary to my research program, and the personnel at every radar facility I visited were very helpful and cooperative. The radar operators, technicians, and meteorologists at the New Orleans and Lake Charles, Louisiana; Athens, Georgia; and Charleston, South Carolina, NWS stations were particularly helpful as were the radar technicians, flight controllers, and meteorologists at the Greenville-Spartanburg and Charleston, South Carolina, FAA stations. Loans of equipment from the Air Force Weapons Laboratory and the Army Night Vision and Electro-optics Laboratory are greatly appreciated. The assistance of serveral of my former and current graduate students has been very valuable, in particular that of Kenneth P. Able, Robert C. Beason, Paul B. Hamel, James J. Hebrard, Harry E. LeGrand, Jr., Frank R. Moore, John P. Nemergut, Thomas J. Sconzo, and Nelwyn L. Stone. Paul B. Hamel was especially helpful in preparation of the final draft of the manuscript. This document represents the final technical report for grant AFOSR 79-0038. I am indebted to the following program managers of the Life Science Directorate at AFOSR who have supported and encouraged my work since 1969: William O. Berry, Domenic A. Maio, Harvey E. Savely, and William G. Wisecup.

Sidney A. Gauthreaux, Jr.
Professor of Zoology
30 April 1980

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

DIRECT VISUAL METHODS FOR DAY AND NIGHTTIME

STUDY OF BIRD MIGRATION

1.1 INTRODUCTION

Many students of bird migration do not have access to radar equipment for use in their investigations, and those that do must from time-to-time make direct visual observations to identify and quantify the birds responsible for the radar echoes. Lowery and Newman (1963) have discussed the use of a spotting telescope to study the daytime and nighttime migration of birds. They recommend that during the day the telescope be directed vertically to sample migrants flying directly overhead and that at night the telescope be trained on the moon to monitor the passage of silhouetted migrants. Although the moon-watching technique (Lowery 1951, Nisbet 1959) has been used successfully in a number of studies of nocturnal migration, the technique is limited to full-moon periods when there is no obscuring cloud cover. In an effort to overcome these limitations a ceilometer technique was developed and tested in the late 1960's (Gauthreaux 1969), and since that time the technique has undergone further improvements. An elaboration of the basic ceilometer technique and subsequent modifications follows.

1.2 ORIGINAL CEILOMETER TECHNIQUE

The ceilometer apparatus as originally described by Gauthreaux (1969) consists of an eight-inch (20 cm) ceilometer lamp (General Electric, PAR 64, 6 volt, 100 watt) connected to a Thordarson or Stancor filament transformer (primary 117/107 volts at 50/60 cps, secondary 6.3 volts, rating of 10 amps), and both are mounted in a box (Figure 1). The apparatus can operate on either line current or battery power. The upright bulb produces a very narrow vertical beam of light, and as migrants aloft fly through the beam they are illuminated from below. When the beams of two ceilometers are superimposed more light reflects from the undersides of birds aloft and higher flying birds can be detected.

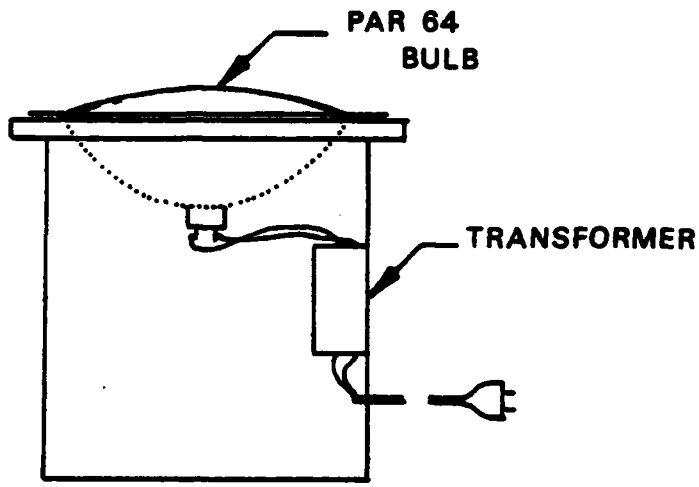

Figure 1. Diagram of the Portable Ceilometer System.

The methods employed for telescopic observations are essentially those described by Lowery and Newman (1963) for daytime observations of the sky. A telescope (or binoculars) is mounted vertically with the space sampled aligned in the vertical lighted cone. The position of the telescope relative to that of the ceilometer determines the altitude at which the telescopic cone will penetrate the light beam. The spread of the ceilometer beam is about 7°; the field width of the 20 × 60 telescope is 2.5°. When the telescope is positioned within five ft (2 m) of the ceilometer, a low-level interference zone of brilliantly illuminated insects and dust particles makes observation difficult. This difficulty can be overcome by moving the telescope 20 - 30 ft (7 - 10 m) away from the ceilometer. Even under the best conditions insects and bats may confuse an observer, but these contaminants are usually identifiable by their manner of flight.

As birds cross the field of the telescope their directions can be recorded in polar coordinates (e.g. N, SW, E), but I suggest that an observer use the clockface method of determining flight directions (Lowery and Newman 1963).

First, the observer must be supine with the body axis aligned north-south so that the head is directed north (the North Star provides a convenient reference point on clear nights). Secondly, the observer must imagine that the circular patch of sky seen through the scope is a numbered clockface with 6 o'clock at the point nearest the observer's feet. The flight paths are recorded in terms of clock points, e.g., "IN" at 6 o'clock and "OUT" at 2 o'clock. Directions can usually be expressed with half-hour accuracy (within ± 7.5°).

The flight directions of birds expressed in clock coordinates can easily be converted to azimuth directions with the aid of Table 1. Because an observer is looking up at the clockface when viewing birds through the telescope, 9 o'clock represents 90° or East, and 3 o'clock represents 270° or West. Thus a bird flying from "3" to "9" in the circular field of view is flying toward a true azimuth of 90° and one flying from "4" to "10" is moving toward 60°. Since 1969 several investigators have used the ceilometer technique (e.g., Hebrard 1971, Lindgren and Nilsson 1975, Avery et al. 1976, and Balcomb 1977), and the technique was further evaluated quantitatively by Able and Gauthreaux (1975).

1.3 ELECTRO-OPTICS AND THE CEILOMETER TECHNIQUE

New developments in the basic ceilometer techinque have markedly enhanced its effectiveness as a research tool for studying nocturnal bird migration. These developments concern the use of an image intensifier (I^2), a low-light level closed circuit television camera (CCTV), a video tape recorder, and a high resolution television monitor.

1.3.1 EQUIPMENT AND METHODS

The key component in the new ceilometer technique is an image intensifier, the AN/TVS-5, manufactured by Varo, Inc., Garland, Texas; the same as Model 340, manufactured by Javelin Electronics, Torrance, California (Figure 2A). This instrument is on loan from the Night Vision Laboratory of the United States Army Electronics Command, Fort Belvoir, Virginia. The AN/TVS-5 image intensifier is a second generation device that is 37 cm long and weighs 3 kg. It has a resolution (lines/mm) of 56 minimum and 64 average, and amplifies ambient light 30,000 times. The intensifier tube diameter is 25 mm (inverter tube - military model MX-9644). The intensifier is equipped with a catadioptric objective lens (focal length 155 mm, T/1.7, f/1.4) that gives a 6.2X

Table 1. The determination of true azimuths from clock face coordinates. Entry points at tops of columns and exit points listed in the columns (e.g., "IN" at 1:00 and "OUT" at 2:00, azimuth equals 225°)

1:00 -	1:30 -	2:00 -	2:30 -	3:00 -	3:30 -	4:00 -	4:30 -	5:00 -	5:30 -	6:00 -	6:30 -
2:00=225.0	2:30=210.0	1:00= 45.0	1:00= 37.5	1:00= 30.0	1:00= 22.5	1:00= 15.0	1:00= 7.5	1:00= 0.0	1:00=352.5	1:00=345.0	1:00=337.5
2:30=217.5	3:00=202.5	3:00=195.0	1:30= 30.0	1:30= 22.5	1:30= 15.0	1:30= 7.5	1:30= 0.0	1:30=352.5	1:30=345.0	1:30=337.5	1:30=330.0
3:00=210.0	3:30=195.0	3:30=187.5	3:30=180.0	2:00= 15.0	2:00= 7.5	2:00= 0.0	2:00=352.5	2:00=345.0	2:00=337.5	2:00=330.0	2:00=322.5
3:30=202.5	4:00=187.5	4:00=180.0	4:00=172.5	4:00=165.0	2:30= 0.0	2:30=352.5	2:30=345.0	2:30=337.5	2:30=330.0	2:30=322.5	2:30=315.0
4:00=195.0	4:30=180.0	4:30=172.5	4:30=165.0	4:30=157.5	4:30=150.0	3:00=345.0	3:00=337.5	3:00=330.0	3:00=322.5	3:00=315.0	3:00=307.5
4:30=187.5	5:00=172.5	5:00=165.0	5:00=157.5	5:00=150.0	5:00=142.5	5:00=135.0	3:30=330.0	3:30=322.5	3:30=315.0	3:30=307.5	3:30=300.0
5:00=180.0	5:30=165.0	5:30=157.5	5:30=150.0	5:30=142.5	5:30=135.0	5:30=127.5	5:30=120.0	4:00=315.0	4:00=307.5	4:00=300.0	4:00=292.5
5:30=172.5	6:00=157.5	6:00=150.0	6:00=142.5	6:00=134.0	6:00=127.5	6:00=120.0	6:00=112.5	6:00=105.0	4:30=300.0	4:30=292.5	4:30=285.0
6:00=165.0	6:30=150.0	6:30=142.5	6:30=135.0	6:30=127.5	6:30=120.0	6:30=112.5	6:30=105.0	6:30= 97.5	6:30= 90.0	5:00=285.0	5:00=277.5
6:30=157.5	7:00=142.5	7:00=135.0	7:00=127.5	7:00=120.0	7:00=112.5	7:00=105.0	7:00= 97.5	7:00= 90.0	7:00= 82.5	7:00= 75.0	5:30=270.0
7:00=150.0	7:30=135.0	7:30=127.5	7:30=120.0	7:30=112.5	7:30=105.0	7:30= 97.5	7:30= 90.0	7:30= 82.5	7:30= 75.0	7:30= 67.5	7:30= 60.0
7:30=142.5	8:00=127.5	8:00=120.0	8:00=112.5	8:00=105.0	8:00= 97.5	8:00= 90.0	8:00= 82.5	8:00= 75.0	8:00= 67.5	8:00= 60.0	8:00= 52.5
8:00=135.0	8:30=120.0	8:30=112.5	8:30=105.0	8:30= 97.5	8:30= 90.0	8:30= 82.5	8:30= 75.0	8:30= 67.5	8:30= 60.0	8:30= 52.5	8:30= 45.0
8:30=127.5	9:00=112.5	9:00=105.0	9:00= 97.5	9:00= 90.0	9:00= 82.5	9:00= 75.0	9:00= 67.5	9:00= 60.0	9:00= 52.5	9:00= 45.0	9:00= 37.5
9:00=120.0	9:30=105.0	9:30= 97.5	9:30= 90.0	9:30= 82.5	9:30= 75.0	9:30= 67.5	9:30= 60.0	9:30= 52.5	9:30= 45.0	9:30= 37.5	9:30= 30.0
9:30=112.5	10:00= 97.5	10:00= 90.0	10:00= 82.5	10:00= 75.0	10:00= 67.5	10:00= 60.0	10:00= 52.5	10:00= 45.0	10:00= 37.5	10:00= 30.0	10:00= 22.5
10:00=105.0	10:30= 90.0	10:30= 82.5	10:30= 75.0	10:30= 67.5	10:30= 60.0	10:30= 52.5	10:30= 45.0	10:30= 37.5	10:30= 30.0	10:30= 22.5	10:30= 15.0
10:30= 97.5	11:00= 82.5	11:00= 75.0	11:00= 67.5	11:00= 60.0	11:00= 52.5	11:00= 45.0	11:00= 37.5	11:00= 30.0	11:00= 22.5	11:00= 15.0	11:00= 7.5
11:00= 90.0	11:30= 75.0	11:30= 67.5	11:30= 60.0	11:30= 52.5	11:30= 45.0	11:30= 37.5	11:30= 30.0	11:30= 22.5	11:30= 15.0	11:30= 7.5	11:30= 0.0
11:30= 82.5	12:00= 67.5	12:00= 60.0	12:00= 52.5	12:00= 45.0	12:00= 37.5	12:00= 30.0	12:00= 22.5	12:00= 15.0	12:00= 7.5	12:00= 0.0	12:00=352.5
12:00= 75.0	12:30= 60.0	12:30= 52.5	12:30= 45.0	12:30= 37.5	12:30= 30.0	12:30= 22.5	12:30= 15.0	12:30= 7.5	12:30= 0.0	12:30=352.5	12:30=345.0

7:00 -	7:30 -	8:00 -	8:30 -	9:00 -	9:30 -	10:00 -	10:30 -	11:00 -	11:30 -	12:00 -	12:30 -
1:00=330.0	1:00=322.5	1:00=315.0	1:00=307.5	1:00=300.0	1:00=292.5	1:00=285.0	1:00=277.5	1:00=270.0	1:00=262.5	1:00=255.0	1:30=240.0
1:30=322.5	1:30=315.0	1:30=307.5	1:30=300.0	1:30=292.5	1:30=285.0	1:30=277.5	1:30=270.0	1:30=262.5	1:30=255.0	1:30=247.5	2:00=232.5
2:00=315.0	2:00=307.5	2:00=300.0	2:00=292.5	2:00=285.0	2:00=277.5	2:00=270.0	2:00=262.5	2:00=255.0	2:00=247.5	2:00=240.0	2:30=225.0
2:30=307.5	2:30=300.0	2:30=292.5	2:30=285.0	2:30=277.5	2:30=270.0	2:30=262.5	2:30=255.0	2:30=247.5	2:30=240.0	2:30=232.5	3:00=217.5
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5:00=270.0	5:00=262.5	5:00=255.0	5:00=247.5	5:00=240.0	5:00=232.5	5:00=225.0	5:00=217.5	5:00=210.0	5:00=202.5	5:00=195.0	5:30=180.0
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6:00=255.0	6:00=247.5	6:00=240.0	6:00=232.5	6:00=225.0	6:00=217.5	6:00=210.0	6:00=202.5	6:00=195.0	6:00=187.5	6:00=180.0	6:30=165.0
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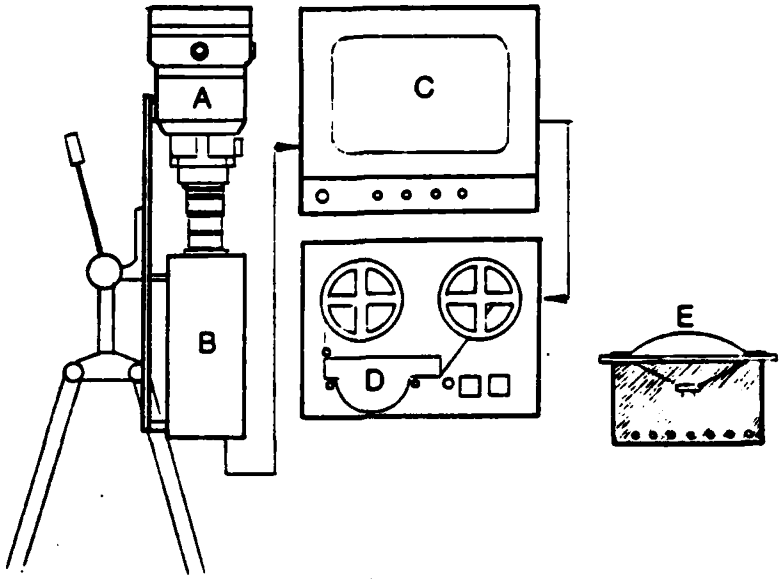


Figure 2. The Image Intensification - Ceilometer System. A) AN/TVS image intensifier, B) video camera, C) video monitor, D) video tape recorder, E) very narrow spot light.

magnification. The instrument has very low distortion and has reduced blooming when a bright light is in the field of view. There is a manual video gain control that regulates the amount of light amplification. The field of view is approximately 9° without the television camera. The field is reduced to a minimum of 3.1° (vertical) when displayed on the television monitor. The unit is powered by two 2.7-volt batteries.

The image intensifier is coupled to a closed circuit television camera, the Hitachi HVC-17LU (AC117V, 60 Hz, 11 watts), that has an excellent response to low light levels (Figure 2B). A Macro-Switar _f_ 1.1, 26 mm lens is attached to the CCTV camera. The quality of the image on the television monitor is adjusted by using the gain and focus on the image intensifier, the _f_ stop and focus on the lens, and the intensity and contrast adjustments on the monitor. The monitor is a Hitachi Video Monitor, VM-126 AU (AC117V, 60 Hz, 37 watts), that has screen dimensions of 178 mm vertical and 240 mm horizontal (Figure 2C). The camera is connected to the monitor with a coaxial cable. The movements of birds aloft in the night sky can be monitored directly from the television screen or the video signal can be routed to a helical scan video tape recorder. I have used a Sony AV-3600 Solid State Videocorder in my work (Figure 2D). The tape (V-30H) provides a continuous 30-minute record; a longer tape can be used for greater recording times.

Because of the cost of the ceilometer lamp bulb and transformer described in the original paper (Gauthreaux 1969), a less expensive bulb (Sylvania 300 watt, 6.6 amp, PAR 64/3, visual approach slope indicator, mogul end prong; or the Sylvania 500 watt, PAR 64/VNSP, extended mogul end prong) is now being used (Figure 2E). These bulbs are superior to the old illumination system because they can be used on line current (125-160/60 AC) directly and they have higher wattage and longer life. During normal operation the vertical light beam is positioned about 60 ft (20 m) from the upright image intensifier. In geographical areas with sufficient ground lighting that reflects skyward (e.g., in cities) the vertical light beam can be eliminated, because the undersides of the migrants aloft will receive sufficient illumination to be readily detected by the image intensifier.

On 26 occasions (10 spring, 16 fall), I was able to evaluate the performance of the image intensifier by moon-watching (Lowery 1951) while gathering image intensification data. Because of the brightening of the sky when the moon is nearly overhead during full moon periods, comparisons were made only when the moon was between 30° and 45° elevation. However, on these occasions the sky was somewhat brighter than during other periods of the lunar cycle, and the contrast in the field of the image intensifier was reduced. Small, high-flying birds in the night sky are sometimes not detected when background contrast is reduced.

1.3.2 RESULTS

The image intensifier-ceilometer technique readily detects even small nocturnal migrants at considerable altitudes above ground level. Although visibility tests of known birds at various distances are presently being conducted, one can get some idea of the altitude of bird targets by examining wing beat frequency, speed, brightness, and size of the image on the television screen. The depth of field of sharp focus gives additional information on the altitudes of the birds. When using the CCTV system with the image intensifier the minimum field of view is 18 ft at 330 ft (5.4 m at 100 m) altitude, 90 ft at 1650 ft (27 m at 500 m), 180 ft at 3300 ft (54 m at 1000 m), and 270 ft at 4960 ft (81 m at 1500 m).

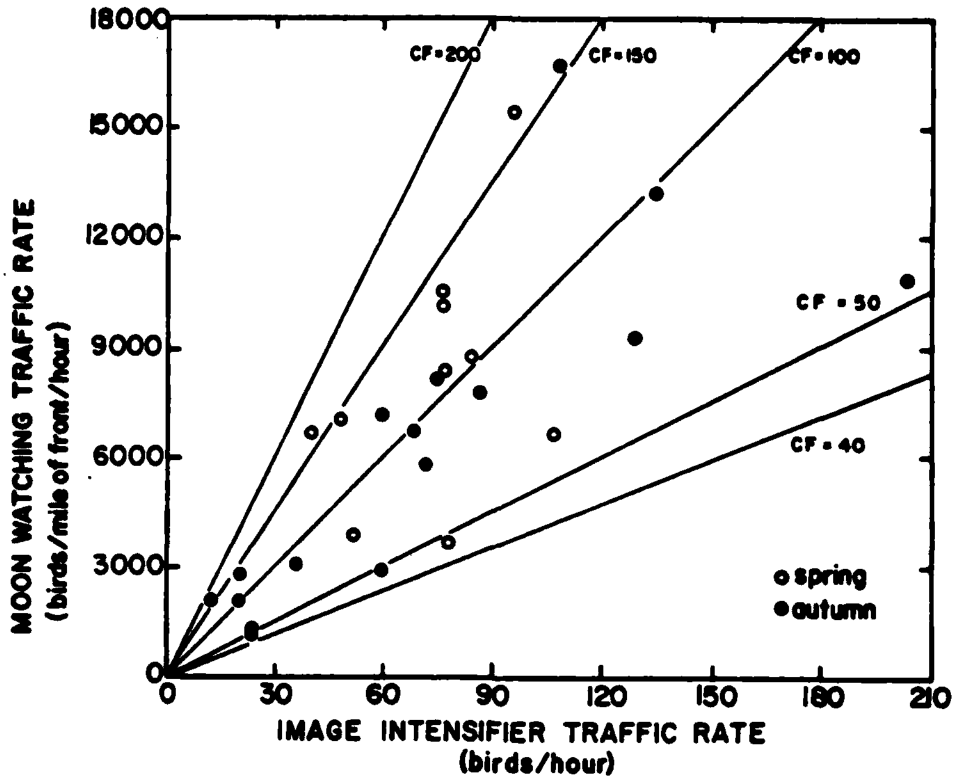


Figure 3. Comparison of Image Intensifier Traffic Rates with Simultaneous Moon-Watching Traffic Rates. CF equals the correction factor applied to the image intensifier traffic rates to equal the moon-watching traffic rates.

Results of the comparison of the image intensifier - ceilometer technique with moon-watching suggest that the two techniques are equally reliable (Figure 3). In order to compute the number of birds crossing a statute mile of front (1.6 km) per hour one must apply a correction factor of 240 to each bird crossing before the disc of the moon directly overhead. To do the same for data gathered with the image intensifier, the correction factor is about 100. Thus by using the image intensifier one can express the amount of migration in terms of a <u>migration traffic rate</u> (birds per mile of front per hour). Equivalent correction factors for determination of migration traffic rates in birds per km of front per hour are 149 for moon-watching and 62 for ceilometer observations.

The direction of migratory movements can be determined directly from the television screen or in the event a more exact analysis is required, one can use a video tape recorder with stop action. By placing a transparent plastic sheet over the TV screen with a circle drawn whose diameter equals the shorter dimension of the screen, one can use a

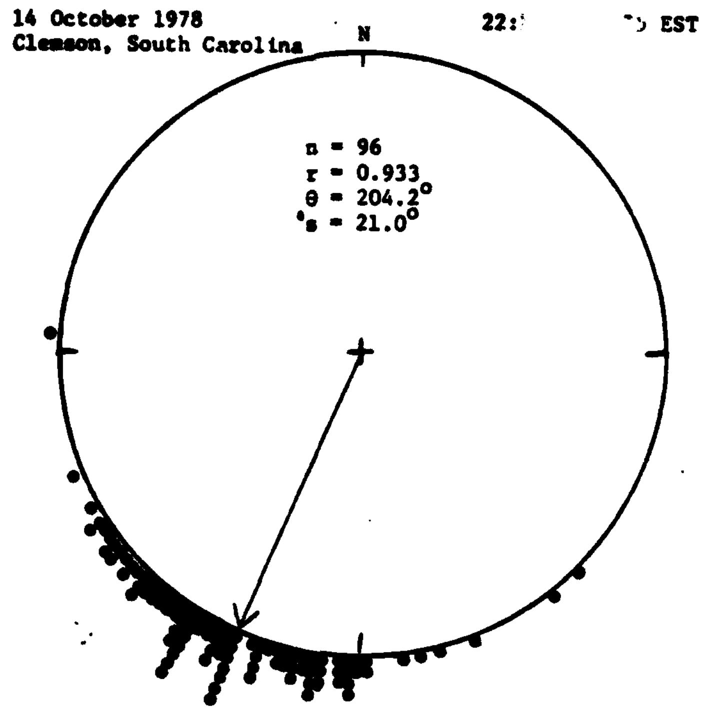


Figure 4. Sample Plot of Flight Directions of Migrants Aloft. n = number of birds, r = length of the resultant vector, θ = resultant direction, and s = the angular deviation.

wax pencil to indicate the path of each bird precisely. Once the sample is completed, the directions can be measured with a protractor and then analyzed (Figure 4).

1.3.3 DISCUSSION

The use of image intensification devices is not new to zoology (e.g., Swanson and Sargeant 1972), but their application to the study of nocturnal bird migration aloft is new. The technique provides quantitative data on the number of migrtants aloft and yields results quite comparable to those obtained by moon-watching (Lowery 1951). Unlike the moon-watching technique, the image intensifier - ceilometer technique can be used on any night and is not dependent upon the presence of the moon and the lack of cloud cover.

One disadvantage of the image intensification system is a lack of exact altitudinal information on the birds detected aloft. If the image intensifier is used in conjunction with a small vertically pointing 3 cm radar such as a shipboard navigation radar (see Hunt 1975), it should be possible to measure exactly the altitudes of the migrants detected by the image intensifier. This approach is currently being developed at Clemson University. The image intensifier-ceilometer system can also be used to monitor the behavior of birds and mammals at night. Swanson and Sargeant (1972) have used this technique to study the nocturnal feeding behavior of ducks; numerous other investigators are employing similar applications.

Chapter 2

RADAR DETECTION AND QUANTIFICATION OF BIRD MIGRATION

2.1 INTRODUCTION AND PURPOSE

When radar units were made sufficiently sensitive to detect distant targets, an unexpected problem resulted. Mysterious radar returns that moved at various speeds and appeared and disappeared with unexplained regularity caused radar operators and technicians great consternation. The mysterious radar echoes were dubbed "angels" by the operators. Not until 1941, when G. C. Varley identified some angel echoes as Gannets (Morus bassanus), large seabirds, flying off the coast of Dover, England, were birds shown to be the source of some radar angels. It is with this event that the field of radar ornithology was established. The developments in the field have been summarized through 1967 by Eric Eastwood (1967) in his book Radar Ornithology, and this area of research is currently producing many important papers with extremely valuable information on the behavior of birds aloft.

The use of radar to detect and monitor weather phenomena and radar's vital role in the detection and control of aircraft are well known, but relatively few radar technicians and operators realize the importance of radar for studies of bird, bat, and insect movements in the atmosphere (Crawford 1949, Geotis 1964, LaGrone et al. 1964, Deam et al. 1965, Eastwood 1967, Williams and Williams 1969, Gauthreaux 1970, 1975, Vaughn et al. 1979). In this report the application of radar to detect and study the movements of birds will be emphasized. The need for such an undertaking is apparent when one examines the figures showing that damages in the millions of dollars are being sustained each year by civilian and military aviation because of bird/aircraft collisions.

Just as there is a need for exact weather information to meet the requirements of air safety, there is a mounting need for similar information on bird concentrations and movements in the atmosphere. This information can be obtained from radar units now operated by the United States National Weather Service and the Federal Aviation Administration. The techniques and information contained in this report should aid radar operators in recognizing the various types of echoes from birds displayed on weather and air-traffic control radars, in estimating the numbers of birds passing over the radar stations, and in gathering information on the altitude of the birds aloft. Use of the following information and techniques by radar operators will greatly benefit aviation interests, both civilian and military, by reducing the number of bird/aircraft collisions and improving flight safety.

2.2 SURVEILLANCE RADARS USED IN BIRD STUDIES

Two types of surveillance radars have been used for intensive studies of bird movements in the United States. One type, the WSR-57, is operated by the National Weather Service; the other, the ASR system, is operated by the Federal Aviation Administration. Both types are located throughout the continental United States and provide an excellent network for monitoring the massive movements of birds during their spring and fall migrations. The major characteristics of the two types of radar systems are summarized in Table 2. Additional details on the ability of ASR radars to detect birds can be found in Flock (1968) and Richardson (1972).

2.2.1 WSR-57 RADAR

The WSR-57 is a 10-cm (S-band) weather radar that is normally operated with a pulse length of 4.0 microseconds (µsec). The shorter pulse (0.5 µsec) has a greater resolution, but because of the pulse repetition frequency and peak power (500 kw) there is a loss of sensitivity. The WSR-57 can detect birds on short pulse only when they are highly concentrated in the air. Although long pulse does not afford good resolution, even very meager movements of birds are readily detected. The WSR-57 has three major advantages for its use in studies of bird migration. Firstly, the radar has a relatively narrow, conical beam (2.0°) which permits the extraction of altitudinal information directly from the plan position indicator (PPI) provided the antenna is tilted 2° to 3°. Secondly, the radar has a range-height indicator (RHI) that permits quick determination of the altitudinal distribution of birds automatically or manually. Thirdly, the radar, because it is a weather radar, has a stepped attenuator (3 db increments) that is normally used to measure the intensity of shower activity within 125 nautical miles (naut.m) (231 km) of the station. The latter feature also permits the measurement of the density of birds aloft in much the same manner as radar meteorologists measure the density and size of rain drops in weather cells. The radar does, however, possess some shortcomings. Because

TABLE 2

CHARACTERISTICS OF WEATHER AND AIRPORT

SURVEILLANCE RADARS USED FOR BIRD STUDIES

Radar	WSR-57M	ASR-4, 5, 6, 7*
band (wavelength)	S(10.35 - 11.10 cm)	S(10.35-11.10 cm)
frequency	2700-2900 MHz	2700-2900 MHz
peak power	500kw	425 kw
pulse length and PRF	0.5 µsec - 658 pps 4.0 µsec - 164 pps	0.833 µsec - 1040 pps - 1170 pps - 1200 pps
polarization	linear	linear and circular
antenna type diameter gain min. detect. sig.	paraboloid 3.7 m (12 ft) 38.6 db -110 dbm	slotted dish 2.7 m (9 ft) high 5.2 m (17 ft) wide 34 db -109 dbm (MTI off) -107 dbm (MTI on)
beam type width	conical 2°	fan (vertical) 1.5° horizontal 5.0° vertical Csc^2 to 30°
range, naut.m range, km	25, 50, 125, 250 46, 92, 231, 462	6, 10, 20, 30, 60 11, 18, 37, 55, 111
ranging accuracy	± 0.5%	± 1.0%
type of sweep	automatic and manual horizontal and vertical either direction. Max 4 rpm; normal 3 rpm	automatic PPI, 15 rpm
presentation (scopes)	PPI off center, PPI, RHI, R, A	PPI off center, PPI
special circuits	STC, isoecho, VIP (some)	MTI, STC-1, STC-2, STC-3, PRF staggering, FTC

* The characteristics are those for ASR-4, but some are also found in the other radars in the series.

of its recovery time, targets within 5 naut.m (9 km) are distorted and difficult to detect. The WSR-57 radar does not have a moving target indicator (MTI), and ground clutter often obscures bird movements taking place within 5 - 10 naut.m (9 - 18 km) of the transmitter site. The ground clutter problem is particularly bothersome in hilly or mountainous areas or at locations where the radar has been placed on top of a tall building in a large city. Side lobing is a major cause of extensive ground clutter when the radar is elevated high above the surrounding terrain, and at such locations it is not unusual for ground clutter to extend outward in most directions for 25 naut.m (46 km). The sweep rate of 20 seconds on the WSR-57 does not permit an observer to look at the PPI and see movement because the old echo from a target has completely disappeared before the next echo is painted. Fortunately, the airport surveillance radars, operated by the Federal Aviation Administration, complement the WSR-57 network.

2.2.2 ASR-4 RADAR

The ASR-4 is only one type of radar in the ASR series, but its use in air traffic control is widespread, offering researchers the opportunity to study bird migration at many localities throughout the United States. The ASR-4 is the ASR radar that has been used most often in studies of bird migrations. The military call the ASR-4 the FPN-47. Although most of my comments in this paper refer to the ASR-4, they also can apply to the rest of the radars in the ASR series.

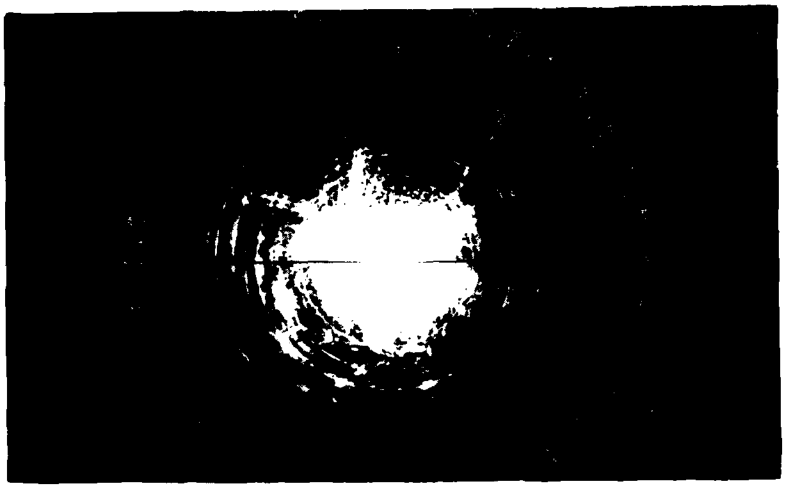
The ASR-4 is an S-band (10.35 - 11.10 cm) radar operating at a frequency of 2,700 - 2,900 MHz at a peak power of 425 kw. The pulse length is 0.833 μsec and the pulse repetition frequencies (PRF's) are 1,040 pulses per second (pps), 1,170 pps, and 1,200 pps. The radar has linear and circular polarization. The antenna type is a slotted dish, 17 ft (5.2 m) wide and 9 ft (2.7 m) high. The antenna gain is 34 db, and the minimum detectable signal without the moving target indicator (MTI) is -109 dbm; with MTI on the minimum detectable signal is -107 dbm. The radar beam is a vertical fan type, 1.5° in the horizontal and 5° in the vertical then cosecant squared from the upper half-power point to 30° elevation. The receiver noise figure is 4.5 db or less (normally 1 to 3 db better than this operating limit). Range in nautical miles is variable from 6, 10, 20, 30, to 60 naut.m, and the ranging accuracy is ± 1.0%. The radar has automatic sweep at 15 revolutions per minute.

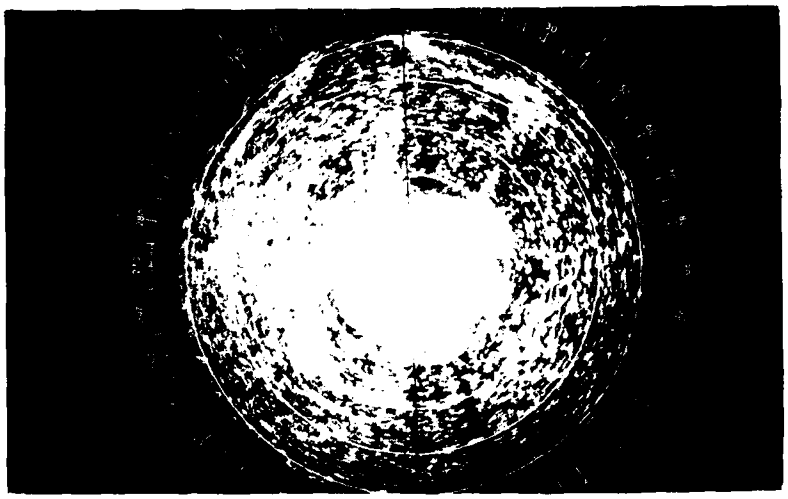
The scope presentation is a plan position indicator (PPI) with off center capability. Originally, the ASR-4 had several special circuits: moving target indicator (MTI), sensitivity time control (STC), cross-sectional sensitivity (CSS-1 and CSS-2), pulse repetition frequency (PRF) staggering, and fast time constant (FTC). A thorough analysis of the circuits and how they influence bird detectability can be found in Richardson (1972). After 1976, CSS circuits were eliminated and replaced by additional fixed value STC circuits.

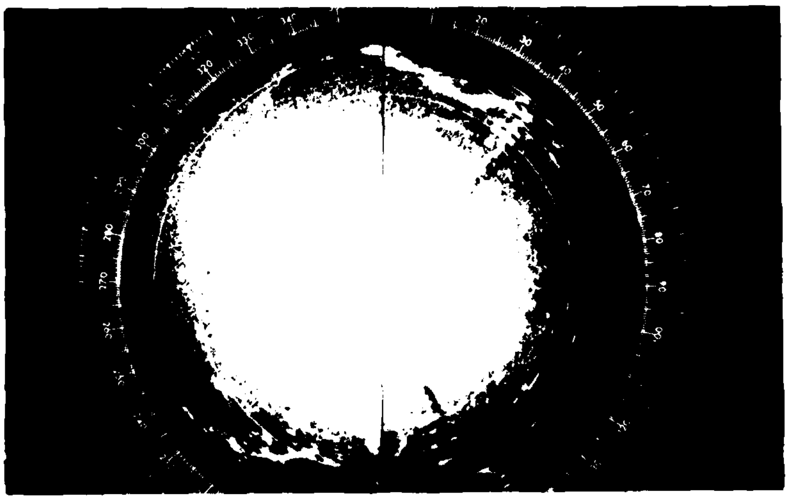
The ASR-4 has three important characteristics lacking in the WSR-57, a radar I have used extensively in previous migration work (Gauthreaux 1970). The combined short pulse length, pulse repetition frequency, and 425 kw peak power give the ASR-4 good resolution of close-in targets. Bird targets within a mile of the transmitter are clearly displayed on the PPI when the PPI is on 6 nautical mile range. The radar is equipped with MTI circuitry that eliminates ground clutter so that only moving targets are displayed. The sweep rate of 15 rpm is fast enough so that an echo does not fade completely before the new echo is painted on the PPI. This results in each moving target having a tail similar in appearance to a shooting star or comet. The "tails" are made up of progressively fainter echoes from previous sweeps of the radar beam. Slower moving targets like birds have rather continuous, short tails, whereas faster targets like aircraft show longer, broken tails. The presence of tails on the echoes gives immediate information on the direction of target movement, and the lengths of the tails give relative ground speeds.

The disadvantages of the ASR-4 for migration studies are bothersome but certainly do not overshadow the radar's beneficial characteristics. The most serious limitation is the lack of detailed range-height capability because of the vertical dimensions of the radar beam. Without accurate altitudinal information, flight controllers would have to vector aircraft around dangerous concentrations of birds even though their altitudes may be widely separated. An additional shortcoming is the absence of a stepped attenuator that can be used to measure the intensity of echoes from birds. Such a measure as will be demonstrated reflects the number of birds aloft or the number of birds in a given flock.

In retrospect, the WSR-57 and the ASR-4 systems truly complement each other. Those characteristics that are not present in one system can be found in the other. If a radar network is to be established to detect and monitor the movements of hazardous bird concentrations throughout the United States, both the National Weather Service and FAA radars should be integral parts of that network.







2.3 TYPES OF RADAR ECHOES FROM BIRDS

When one views the radar screen of the WSR-57 or ASR-4 on most nights, particularly at short ranges during the spring and fall months, one immediately notices a typical display of numerous small echoes distributed out from the center for several nautical miles in all directions. Such displays on the WSR-57 frequently have the characteristics of echoes from light rain. On the ASR-4 the displays are made up of numerous fine dot echoes distributed in a "figure-8" or hourglass pattern when the MTI is operating. These patterns are typical displays produced by hundreds to thousands of birds migrating to their northern breeding grounds during the spring and to their wintering grounds in the tropics and the southern United States in the autumn.

Since 1963 I have made telescopic and binocular observations of the sky during the day and of the moon at night at selected radar stations during the gathering of information on radar displays in an effort to identify the types and numbers of birds responsible for the radar echoes. When no moon was available at night, I watched with a telescope or binoculars the movement of birds aloft as they flew through the light of a vertical ceilometer beam (see Chapter 1). Most observations were made near the radar installations. On a few occasions watches were made 12 - 15 naut.m (19 - 24 km) from the station. To identify the birds responsible for the radar echoes, the following correlations were determined:

1. the density of birds observed and the density of echoes on radar;

2. the direction of bird movement aloft and the direction of echo movement on radar; and

3. the flock structure of birds aloft and the size and distribution of echoes on radar.

In all cases the correlations between the birds actually observed through binoculars and telescopes and the echoes on radar attributed to birds were extremely high.

+Figure 5. PPI of the WSR-57 Radar at New Orleans, Louisiana, on 25 naut.m (46 km) Range. (A) 10 May 1967, 22:11 CST, 2.5° antenna elevation, no migration. (B) 22 April 1967, 16:54 CST, 3.0° antenna elevation, daytime migration. (C) 22 April 1967, 20:17 CST, 2.5° antenna elevation, nocturnal migration.

2.3.1 WSR-57 RADAR

On nights with no bird migration, the radar screen of the WSR-57 shows only ground returns (Fig. 5). The appearance of nocturnal bird migration on the WSR-57 during most of the night is noticeably different from that in the last part of the night and during the day. At night the WSR-57 radar screen displays extensive areas of diffuse, stippled (sugar-like) echoes with a few larger, brighter echoes scattered over the dark disc (Fig. 5C). According to the simultaneous direct visual observations, the small sugar-like echoes represent landbirds flying individually in the night sky, while the larger, brighter echoes represent tight flocks of shorebirds and waterfowl in nocturnal migration. As night progresses the echo pattern on the screen changes from diffuse, stippled echoes to larger, dot echoes. A drop in the quantity of migration is correlated with the appearance of coarse dot echoes late in the night.

The daytime echoes on the WSR-57 are generally strong and persistent and remain visible on the radar screen for a distance of several nautical miles. The density of these echoes rarely causes saturation of the radar screen except at certain geographical localities such as along the northern coast of the Gulf of Mexico during spring migration. The dot echoes that appear on radar during daylight hours are caused by several types of birds flying in flocks or groups. Along the northern coast of the Gulf of Mexico most dot echoes are caused by flocks of small landbirds (Passerines) arriving during the afternoon from over the Gulf after a spring trans-Gulf migration (Fig. 5B). Other dot echo patterns on the PPI during the day are caused by flocks of ducks and geese (Fig. 6), flocks of shorebirds (Fig. 7), and thermals with groups of hawks or vultures. Frequently at dawn during the late fall, winter, and early spring, areas of doughnut echoes or concentric circular echoes elaborate on the radar screen. These are produced primarily by blackbirds (Icteridae) and Starlings (*Sturnus vulgaris*) departing from overnight roosts in successive bursts. In the late afternoon these birds form extensive flocks in long lines and return to the roosting site in a somewhat staggered fashion, producing large echoes on the radar screen converging at the roost site.

2.3.2 ASR-4 RADAR

On 6 and 10 naut.m (11 and 18 km) range the ASR-4 should be able to distinguish targets separated by as little as 615 ft (187 m) in the horizontal. Because of this resolution individual birds aloft commonly produce sharp, distinct echoes. On nights with little bird movement, the PPI of the

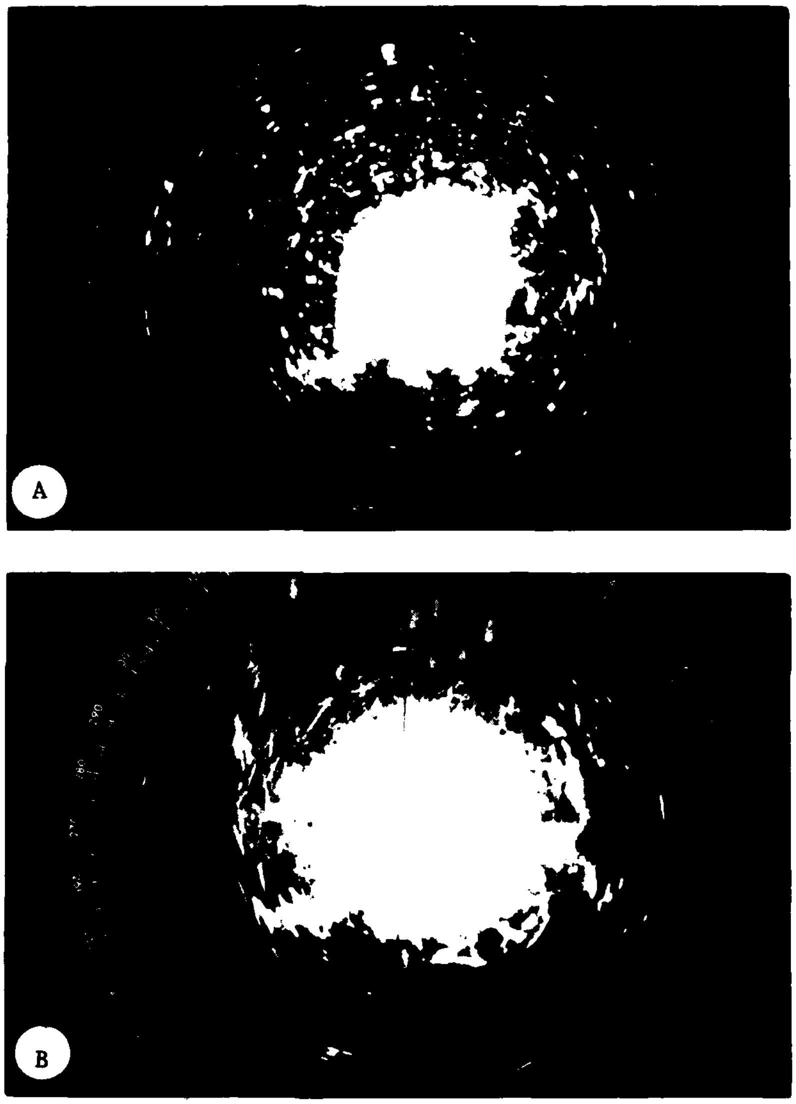


Figure 6. Echoes from Flocks of Ducks and Geese on the PPI of the WSR-57 Radar at Lake Charles, Louisiana, on 14 March 1965. (A) single revolution of antenna, 17:47 CST. (B) 5-minute time exposure for 15 revolutions from 18:47 to 18:52 CST. Larger echoes are from flocks of 100-200 geese, smaller echoes are from flocks of 4-10 ducks. Antenna elevation is 2.5°, range is 25 naut.m (46 km), and STC is off.

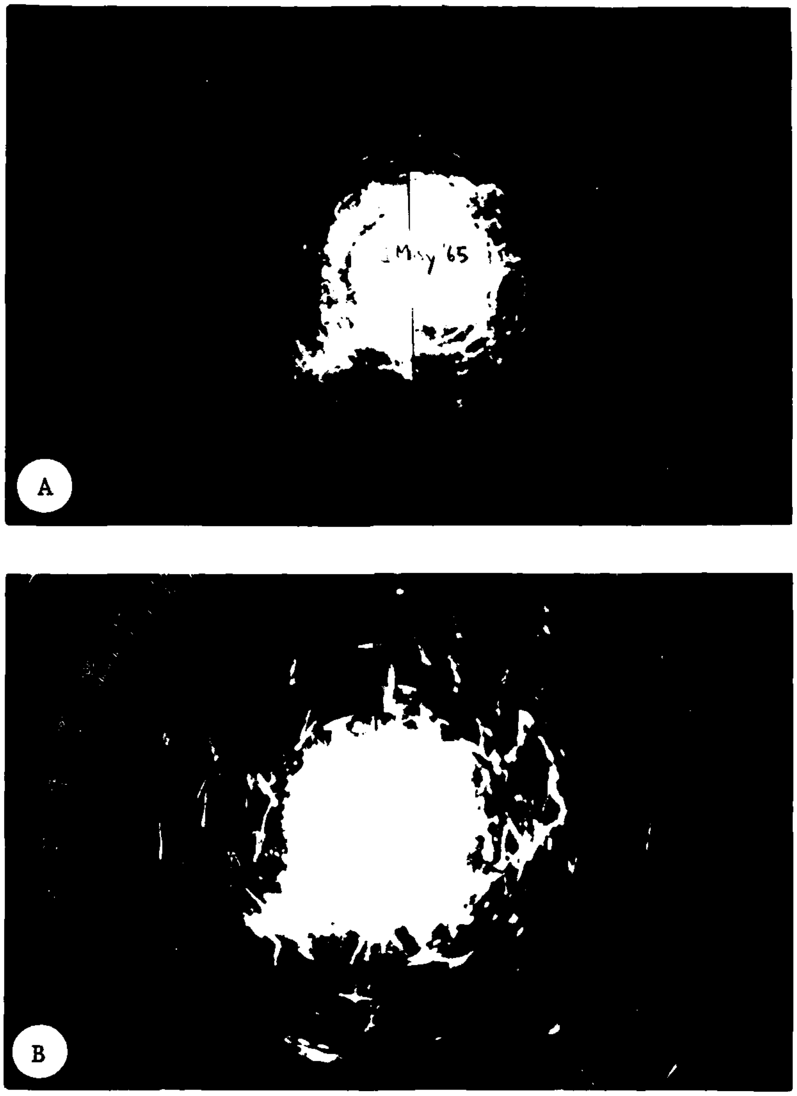


Figure 7. Echoes from Flocks of Large Shorebirds on the PPI of the WSR-57 at Lake Charles, Louisiana, on 1 May 1965. (A) single revolution of the antenna, 18:17 CST. (B) 5-minute time exposure for 15 revolutions from 18:18 - 18:23 CST. Antenna elevation is 3.0°, range is 25 naut.m (46 km), and STC is off.

ASR-4 shows only isolated bird echoes near the center of the display (Fig. 8A). The scan rate of 15 rpm gives the echoes "tails" resulting from the progressive decay of previously registered echoes. In Figure 8A the tails are particularly evident.

As the number of birds flying aloft increases, the pattern on the PPI changes significantly. On 6 naut.m (11 km) range one can see the influence of the moving target indicator (MTI). It produces a wedge or band through the center of the PPI where noticeably fewer bird echoes are displayed (Fig. 8B). The wedge is always oriented perpendicular to the direction of echo movement and is the result of birds being eliminated at the point where they have a minimal radial velocity, a point where their flight paths are tangential to the sweep of the beam. In Figure 8B the wedge is between the azimuths of 60° and 240°. On greater ranges bird echoes produce a characteristic pattern that can be called the "figure-8" or hourglass display (Fig. 8CC). Because most flight controllers use the ASR-4 on ranges between 20 and 60 naut.m (67 and 111 km), this display is the one that they will encounter when dense bird migrations are underway at night. The pattern is produced by large numbers of songbirds flying individually in the night sky.

Figure 9A shows the PPI of the ASR-4 when isolated flocks of ducks containing 8-10 individuals are migrating, and Figure 9 shows flocks of shorebirds moving early in the evening before the echoes from smaller songbirds increase in number on the PPI. The larger echoes from ducks and shorebirds move at faster speeds (airspeeds of 30 - 45 knots [55 - 85 km/hr; kph]) than do songbirds (15 - 25 knots [28 - 46 kph]), and the larger echoes often appear on the radar screen near the time of sunset when there is still enough twilight to see ground objects distinctly. Shortly after dark even though flocks of ducks and shorebirds are still on the PPI, they are largely obscured by the numerous echoes from the smaller songbirds. On the average, the larger, faster flying birds that produce larger dot echoes fly higher than the smaller, slower flying birds that produce the numerous small dot echoes (see subsequent section on altitude).

2.4 COUNTING BIRDS WITH SURVEILLANCE RADARS

Despite the ever increasing use of radar in work on bird movements, the problem of estimating bird densities from echo densities on the radar screen persists. Nisbet (1963) was first to devise a radar quantification technique based on the decrease in the number of bird echoes with increasing range, but his method cannot be used when heavy migrations are underway. This section reports on the development of a radar technique for quantifying bird movements. It is based on the correlation between the attenuation of reflected radar signals from the population of birds aloft and the actual number of birds involved as determined by direct visual techniques. The approach is similar to that used to count birds departing a roost in England (Eastwood et al. 1962). A preliminary description of the technique of quantifying the amount of bird migration with the WSR-57 has already been published (Gauthreaux 1970), and the quantification of bird densities with ASR-4 radar has recently been described (Gauthreaux 1974).

2.4.1 WSR-57 RADAR

2.4.1.1 Bird Detectability with the WSR-57 Radar

The attenuation of pulsed radar signals reduces the number of perceptible returns because of the distribution of the number of targets among the radar resolution cells or pulse volumes. The pulse volume is computed from the pulse length of the radar signal and the beam width. All targets contained in a single pulse are unresolved and are recorded on the radar screen as a single point echo. The pulse volume is not constant but increases with distance from the antenna. For this reason, only attenuation readings made at the same range should be compared.

Konrad et al. (1968) have given the mean cross sections of several different species of birds on 10-cm radar. Examples are the Boat-tailed Grackle (Cassidix mexicanus), 23 cm^2; House Sparrow (Passer domesticus), 12 cm^2; and Rock Dove (Columba livia), 80 cm^2. Eastwood (1967) has given the radar cross sections of a number of European birds as measured with a 10-cm radar. The Chiffchaff (Phylloscopus collybita), a small sylviid, has a radar cross section of 8 cm^2, while the Starling has a cross section of 34 cm^2. At 10 naut.m (18 km), the WSR-57 can detect a target with a radar cross section of 17 cm^2 (Gauthreaux 1968). When a resolution cell at this range contains one bird with a cross section of 17 cm^2 or greater, an echo will be produced on

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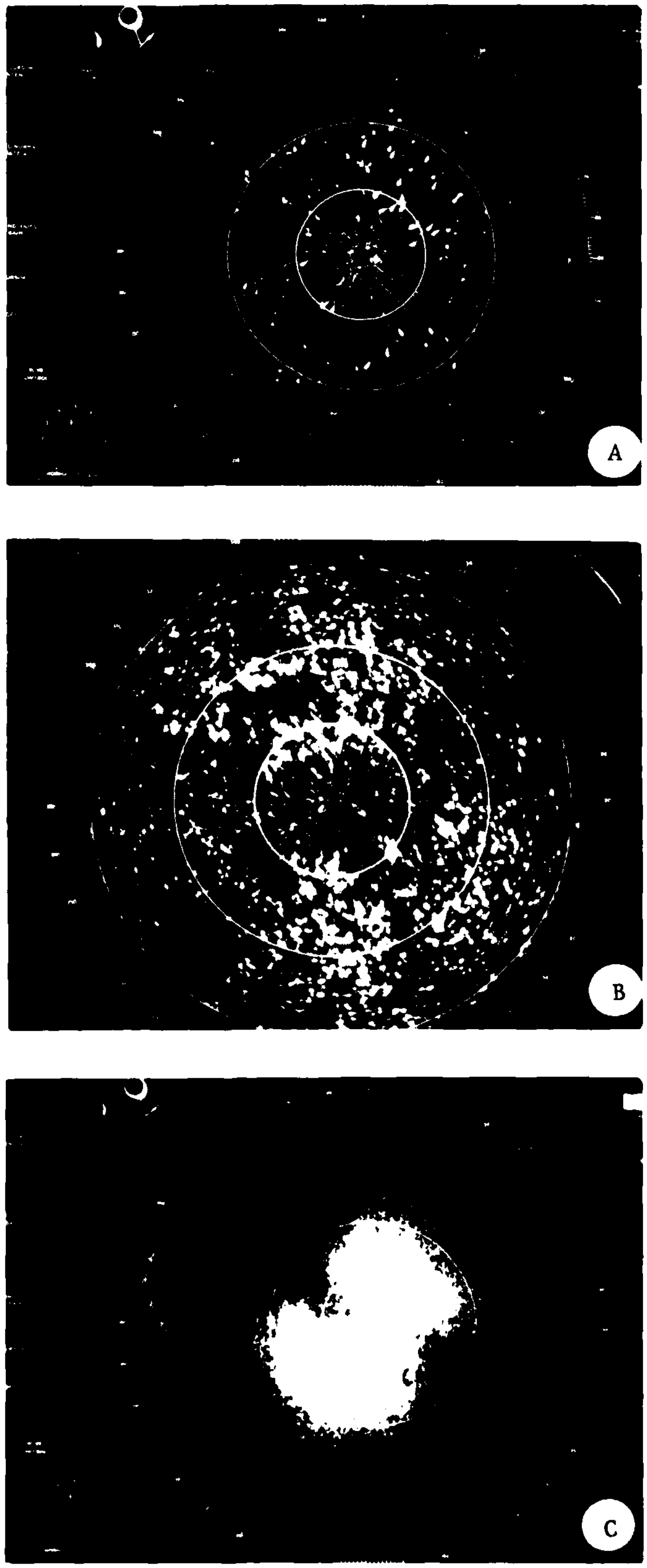
Figure 8. The ASR-4 at Greenville Municipal Airport, South Carolina. (A) 15 May 1973, 20:15 EST, 6 naut.m (11 km) range, MTI and CSS-1 on, IF gain high. (B) 24 March 1973, 22:17 EST, 6 naut.m (11 km) range, MTI on, STC and CSS off, IF gain high. (C) 29 April 1973, 20:55 EST, 20 naut.m (37 km) range, MTI and CSS-1 on, IF gain high.


A
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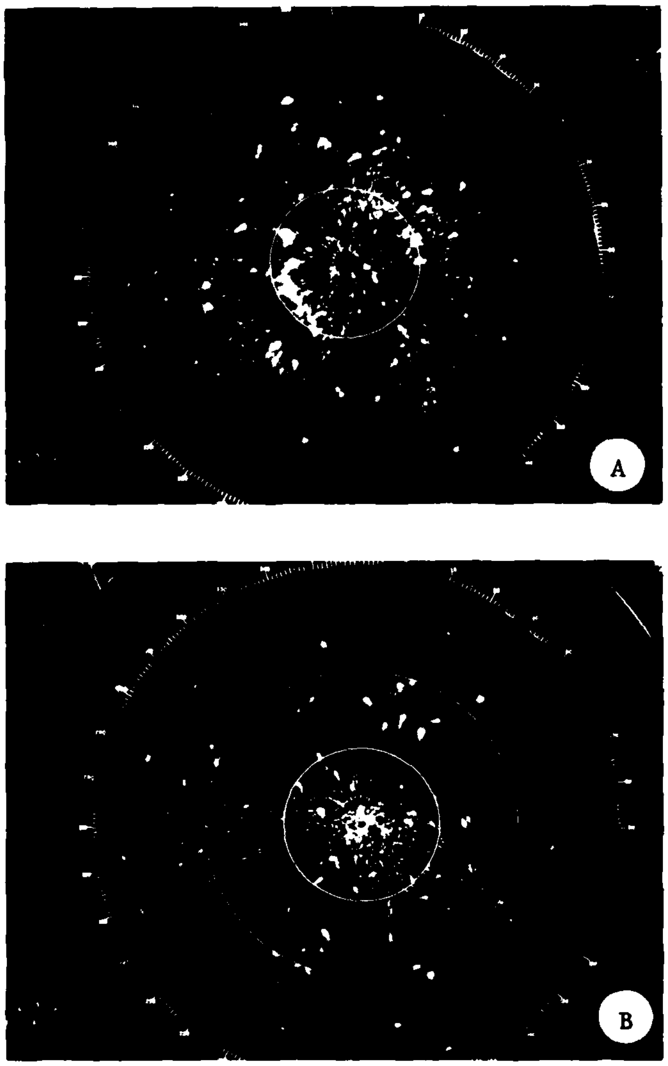

Figure 9. Flocks of Ducks and Shorebirds Displayed on the PPI of the ASR-4 Radar at Greenville, South Carolina. (A) 15 May 1972, 19:37 EST, 6 naut.m (11 nm) range, MTI on, STC off, IF gain high. (B) 10 April 1973, 20:44 EST, 6 naut.m (11 km) range, MTI on, STC and CSS off, IF gain high. Flocks of unidentified shorebirds.

the radar screen from that pulse volume. When smaller birds with smaller cross sections are involved, the total of the cross sectional areas must be 17 cm^2 before an echo will register. Once all pulse volumes reach their response level (PPI saturation with echoes), additional birds in the pulse volumes will not change the visible radar pattern, but the reflected energy returned to the radar receiver will increase. With attenuation the reflected energy is lessened until certain resolution cells fail to return sufficient energy to produce an echo, thus breaking the solid area of echoes on the radar screen.

2.4.1.2 Quantification of Bird Movements with the WSR-57 Radar

Figure 10 shows the density scales used to evaluate the density of bird echoes on the radar screen of the WSR-57. The separate scales reflect the difference between the types of bird echoes that most frequently appear on the radar screen during the day and at night. Each of the five diurnal reference patterns of Figure 10 is composed of comparatively large dot echoes, the type characteristic of daytime migration. These echoes are strong and persistent and can be tracked on the radar screen for distances of 2 - 6 naut.m (3.5 - 11 km). Their density infrequently causes saturation ofthe PPI, and separate echoes can usually be distinguished. Occasionally, several dot echoes will merge and form an isolated solid area of echoes. Finer echoes are often distributed among the larger ones. Figure 5B shows the characteristic pattern of bird echoes on the PPI of the WSR-57 during the day. Figure 5C shows the characteristic PPI presentation when numerous small birds are migrating at night.

Simultaneous telescopic and binocular observations have shown that flocks of passerine birds produce most of the dot echoes during the day, but flocks of shorebirds and non-passerine landbirds contribute a few of the echoes. Individual migrants cause the scattered fine echoes in the daytime radar patterns. The daytime aggregations of passerines range from two to three individuals to more than 100 individuals, and the average flock size is 20 birds. The largest flock observed during daytime telescopic and binocular watches was estimated as 175 birds. The average numbers of flock echoes within a 5 × 5 naut.m (9 × 9 km) sample square for each of the diurnal density patterns in Figure 10 are 10 for pattern 1, 30 for pattern 2, 40 for pattern 3, 60 for pattern 4, and 90 for pattern 5.

With attenuation it is possible to estimate roughly the sizes of daytime flocks and the frequency of each flock size. Since the daytime density patterns have numerical

RADAR DENSITY PATTERNS

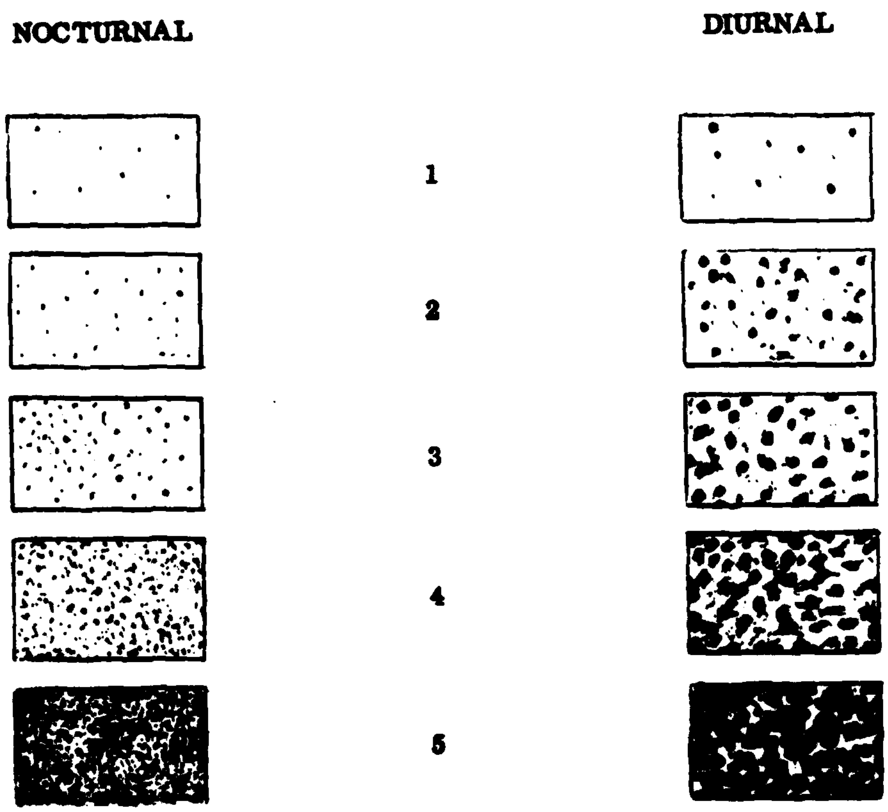

Figure 10. Radar Density Patterns Used to Evaluate Densities of Bird Echoes on the PPI of the WSR-57.

equivalents, each time the density of flock echoes changes with added attenuation, the number of eliminated flocks can be computed. The amount of attenuation required to eliminate a flock echo is related to both the number of birds in the flock and the size of the birds. If 3 db will eliminate all flocks containing 2-4 birds of 17 cm^2 radar cross section at 10 - 15 naut.m (18 - 28 km) range, the remaining dot echoes displayed on the PPI must have more than 2-4 birds per flock. Table 3 gives the relative abundance of flock sizes determined by attenuation during studies of migration in coastal Louisiana. This distribution assumes that the vast majority of passerine migrants aloft during the day in coastal Louisiana in April have <u>on the average</u> a radar cross section of 17 cm^2. When predominantly larger birds are migrating, the flock sizes will be overestimated. The average flock size of 20 birds computed from telescopic and binocular observations agrees well with the median flock size determined by attenuation.

TABLE 3

DAYTIME FLOCK SIZES AS DETERMINED BY ATTENUATION

BASED ON MINIMUM DETECTABLE CROSS SECTION

OF 17 CM^2 AT 10 NAUTICAL MILES (18 KM)

Number of birds/flock	Number of flocks	Percentage of total
2-4	40	5.0%
5-6	175	22.5%
7-12	135	17.6%
13-25*	140	18.0%
26-50	135	17.2%
51-100	75	9.5%
101-200	60	7.7%
200+	20	2.5%

* Computed median flock size = 19 birds/flock

Fine, dust-like echoes are characteristic of movements of passerine birds flying singly in the night sky (Fig. 5C). The fine echoes are usually so dense that they saturate the PPI within the 20 naut.m (37 km) range mark. Once the radar screen is saturated with echoes, additional echoes cannot be displayed even though migration traffic rates (the number of birds crossing one statute mile [1.6 km] of front per hour) increase. In order to determine the approximate number of birds aloft once the PPI is saturated with bird echoes, the radar's stepped attenuator can be used. By attenuating in increments of 3 db the solid or saturated area of echoes changes until it matches closely density pattern 4 in the nocturnal series of Figure 10 The amount of attenuation required to do this is recorded. Density pattern 4 was chosen as the base reference pattern for all attenuation readings because the pattern is easily identifiable on the radar screen, and the abundance of fine targets in the pattern precludes the possibility of attenuating until only echoes from isolated flocks and scattered large birds remain on the radar screen. Although attenuation changes the entire echo pattern on the radar screen, the only attenuation information used in the quantification procedure is that gathered within a 2 × 5 naut.m (4 × 9 nm) area between the range limits of 10 - 12 naut.m (18 - 22 km) and perpendicular to the direction of migratory movement. This area on the PPI covers an altitudinal stratum of approximately 2500 ft (760 m) from 1750 - 4500 ft (530 - 1370 m). The antenna tilt is adjusted so that nearly all the migrants aloft are in this altitudinal zone.

To translate the attenuation information into numbers of migrating birds, simultaneous moon-watching traffic rates (MTR) were compared with the amounts of attenuation required to reach pattern 4. The methods followed for the telescopic observations of the moon are essentially those described by Lowery and Newman (1963). The telescope (either a 20X or 30X Bausch & Lomb BALscope, Sr., or a 40X Questar) was trained on the moon, and as the silhouettes of birds crossed the disc, their direction was recorded in terms of clock face numbers (e.g. "3" to "9"). The resultant data were analyzed using the methods of Nisbet (1959). The final figures express the estimated number of birds crossing one statute mile (1.6 km) of front per hour and are called migration traffic rates (MTR). When the moon was not available because of cloud cover or the phase of the lunar cycle, 20 × 60 or 10 × 50 binoculars were pointed up a ceilometer beam and the passage of migrating birds was observed. This technique (Chapter I) yields information on the types of birds

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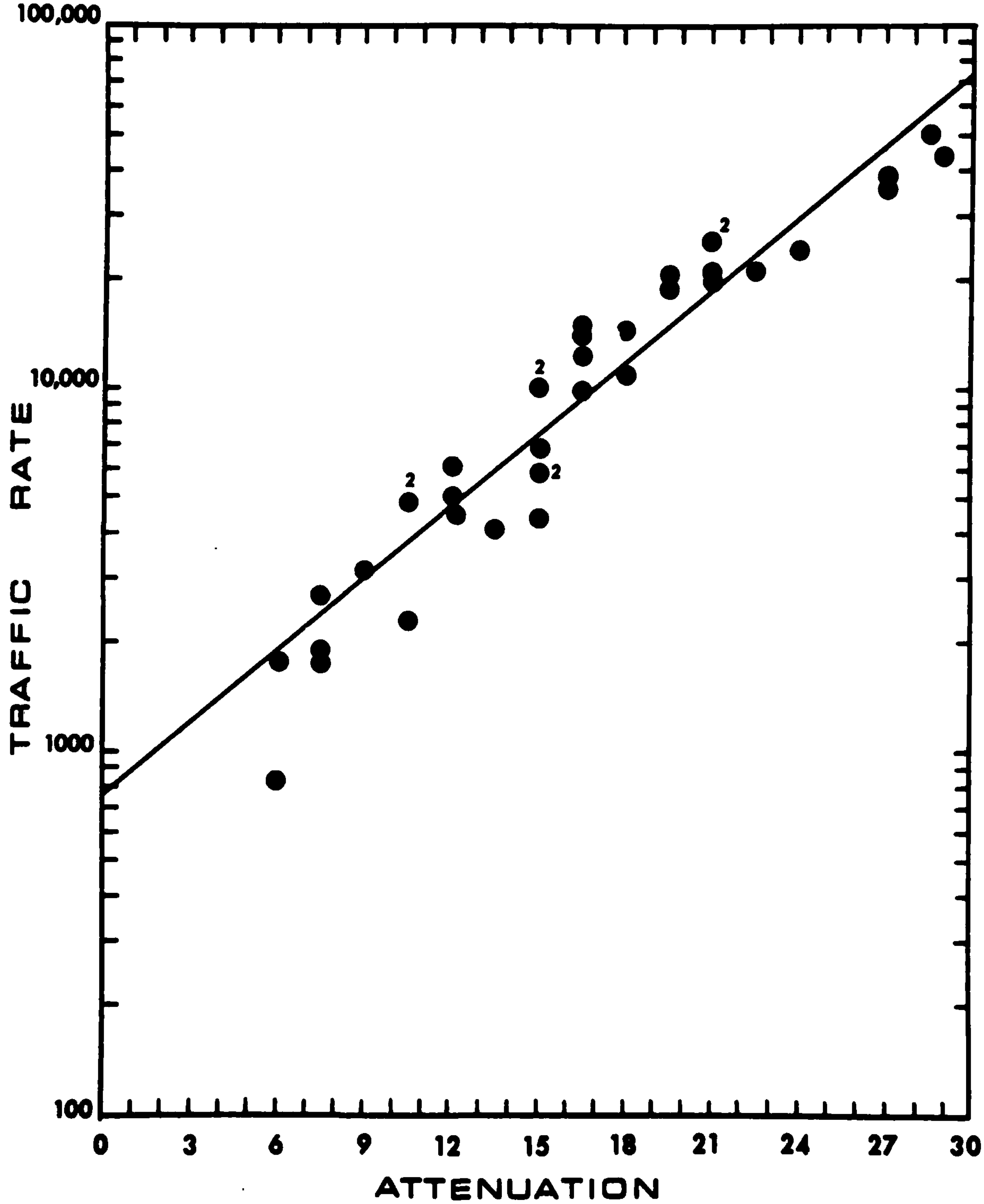
Figure 11. The Attenuation - Traffic Rate Relationship for Nocturnal Migration. Nocturnal density pattern 4 was used as the reference base.


100,000
10,000
1000
100
TRAFFIC RATE
0
3
6
9
12
15
18
21
24
27
30
ATTENUATION
2
2
2
2

migrating and their numbers, and this technique has been evaluated in terms of its contribution to the quantification of radar displays of migration (Able and Gauthreaux 1975).

Figure 11 shows the relationship between the amount of attenuation required to reach density pattern 4 of Figure 10 and the equivalent migration traffic rates as determined by moon-watching. The data were gathered on 19 nights during spring and fall full-moon periods from 1969 to 1972 at the WSR-57 radar stations at Athens, Georgia, and Charleston, South Carolina. The correlation coefficient is +0.95 ($p<0.001$, $N=37$), and the relationship is given by the formula:

$$\log_{10} (\text{traffic rate}) = 0.066 \times (\text{attenuation}) + 2.880.$$

The y-intercept, 759 birds per mile of front per hour (474 birds per km of front per hour), is the moon-watching traffic rate that is equivalent to density pattern 4. Thus the amount of migration aloft can be computed using the stepped attenuator on the WSR-57 and Figures 10 and 11

2.4.2 ASR-4 RADAR

2.4.2.1 Bird Detectability with the ASR-4 Radar

Although it is well known that the ASR radars can detect birds (Flock 1968; Richardson 1972), little has been mentioned concerning the radar's ability to detect birds of various radar cross-sectional areas at various ranges. In this section a theoretical basis for bird detectability and quantification of migratory movements aloft will be established.

First one must compute the radar constant for the ASR-4, using the following equation:

$$(1) \qquad R_c = \frac{1.1 \times 10^{-23}\ P\ G^2\ \theta^2\ \tau}{\lambda^2}$$

where P_o is the transmitted peak power in watts (4.25×10^5),

G is the antenna gain in watts (2,550), θ is the beam width in degrees assumed symmetric ($1.5° \times 5° = 7.5°$), τ is the pulse duration (0.833 μsec), and λ is the wavelength in cm (10). When these quantities are used in the equation, the radar constant equals 1.89×10^{-12}.

The calculation for the minimum detectable cross-section at a given range for the ASR-4 uses the radar equation:

$$A = \frac{P_{min}\ r^4}{R_c\ G^2} \qquad (2)$$

where A is the radar cross-sectional area of the bird, P_{min} is the minimum detectable power for received echoes (5.02×10^{-23}), r is the range in nautical miles, R_c is the radar constant, and G^2 is the antenna gain squared (6.5×10^6).

Evaluation of the equation at various ranges gives the cross-sectional areas that will just produce an echo at the respective ranges (Table 4).

TABLE 4

CROSS-SECTIONAL AREAS OF BIRDS REQUIRED

TO PRODUCE AN ECHO ON ASR-4 AT VARIOUS RANGES

Range, naut.m (km)	Cross-sectional area (cm^2)
2 (3.7)	6.5×10^{-3}
4 (7)	1.04×10^{-1}
6 (11)	5.3×10^{-1}
8 (15)	1.68
16 (30)	26.8

These figures have little meaning until they are associated with birds of known cross-sectional areas. Edwards and Houghton (1959) have presented the cross-sectional areas of several species of birds, and more importantly their data

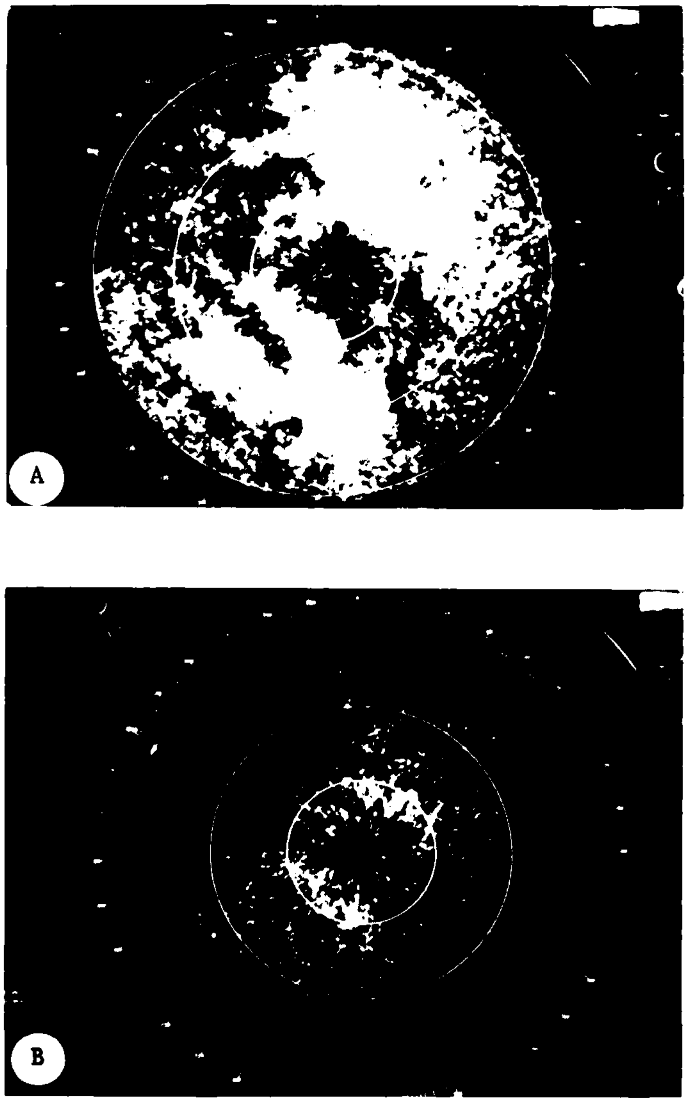


Figure 12. Radar Photographs of the ASR-4 at Greenville, South Carolina, Illustrating the Effects of the CSS-1 Circuit. MTI on, IF gain high, and 6 naut.m (11 km) range. (A) 6 April 1973, 22:32 EST, STC and CSS circuits off. (B) 6 April 1973, 22:07 EST, CSS-1 on.

show how the orientation of the birds in space with respect to the radar beam changes the birds' cross-sectional areas. Table 5 shows this nicely.

TABLE 5

SELECTED RADAR CROSS-SECTIONS OF BIRDS*

Species	Broadside (cm^2)	Head (cm^2)	Tail (cm^2)
Pigeon	30	1.5	1.1
Starling	11	2.0	1.3
House Sparrow	5	0.3	0.2

*data from Edwards and Houghton (1959)

As can be seen from Table 5, a bird approaching the radar head-on has a dramatically smaller radar cross-sectional area than one passing tangential to the radar beam. On the ASR-4 when the MTI is engaged, only those birds heading more or less toward or away from the radar are displayed; those with less radial velocity are cancelled by the MTI. It is therefore important to note that the head and tail cross-sections are the important ones when one is working with the ASR-4 with MTI on. If one compares the data in Table 4 and Table 5 it is apparent that a single pigeon (<u>Columba livia</u>) flying toward the radar should theoretically produce an echo on the ASR-4 at 6 naut.m (11 km) range but not at 8 naut.m (15 km) range. Similarly, a single House Sparrow (<u>Passer domesticus</u>) moving toward the radar should produce an echo at 4 naut.m (7 km) range but not at 6 naut.m (11 km) range.

2.4.2.2 Quantification of Bird Movements on the ASR-4 Radar

For the ASR-4 the minimum range separation between two targets which can exist and still make resolution possible on the PPI is 410 feet (125 m). The minimum asimuth resolution is a function of the beam width and range, and it is equal to 0.039 R, where R is the range.

If one assumes that the migrants aloft are rather regularly spaced in a horizontal plane, then it is possible to calculate the number of migrating birds that will just cause saturation of the radar screen based on range and azimuth resolution. At 2 naut.m (3.7 km) range, 189 birds equally spaced in a square nautical mile (3.4 km^2) is the maximum detectable number without saturating that area on the PPI. This is approximately equivalent to 3,800 birds crossing a nautical mile (1.8 km) of front per hour and moving toward the radar station at a ground speed of 20 knots (37 kph). At 2 naut.m (3.7 km) range virtually all birds aloft will produce echoes on the radar screen. At 4 naut.m (7 km) range, despite poorer azimuth resolution, the power loss per unit cross-sectional area at that range dictates that a traffic rate of approximately 40,000 birds crossing a nautical mile (1.8 km) of front per hour moving toward the radar station at a ground speed of 20 knots (37 kph) is required to saturate one square nautical mile (3.4 km^2). In other words, 2,000 birds per square nautical mile (3.4 km^2) will just saturate one square nautical mile (3.4 km^2) at a range of 4 naut.m (7 km). For a display at 4 naut.m (7 km) range to appear similar to one at 2 naut.m (3.7 km) range, approximately 16 times as many birds must be at 4 naut.m (7 km) range; this is because of the 4th power law (see Skolnik 1970). These figures agree well with those obtained empirically by direct visual quantification of ASR-4 radar displays (Gauthreaux 1973, 1974). During the latter study 3,000 to 4,000 birds crossing a mile of front (2050 - 2750 birds crossing a km of front) per hour usually saturated the radar screen at ranges where all individual birds had sufficient radar cross-sections to return echoes.

Because of the resolution of the ASR-4 at short ranges, individual birds aloft commonly produce sharp, distinct echoes. On nights with little bird movement, the PPI of the ASR-4 shows only isolated bird echoes near the center of the display (Figure 8A). The scan rate of 15 rpm (13 rpm for the ASR-1) gives the echoes "tails" resulting from the progressive decay of previously registered echoes. In Figure 8 the tails are particularly evident.

As the number of birds flying aloft increases, the pattern on the PPI changes significantly. On 6 naut.m (11 km) range one can see the influence of the moving target indicator (MTI). It produces a wedge or band through the center of the PPI where noticeably fewer bird echoes are displayed

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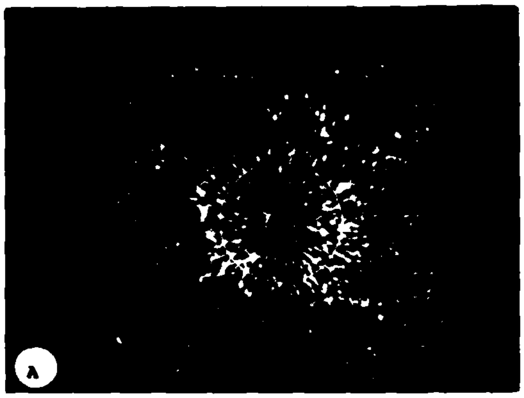
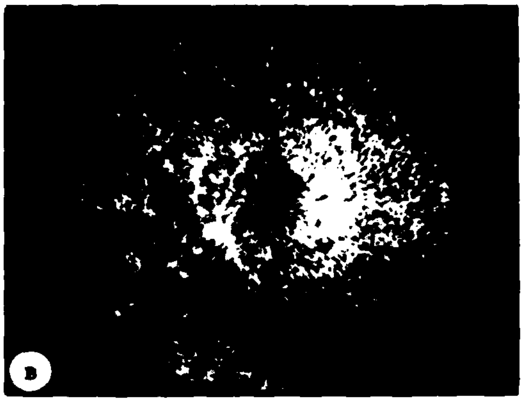
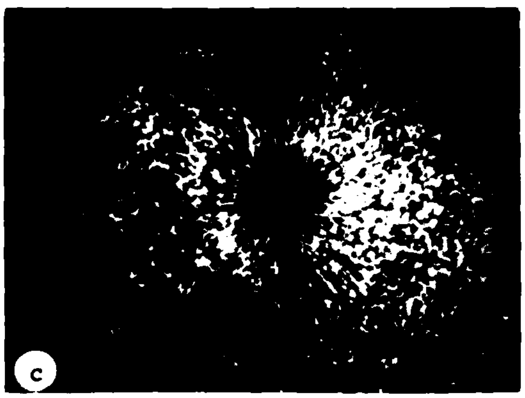
Figure 13. Photographs of the PPI of the ASR-4 on 6 naut.m (11 km) Range Showing Different Densities of Echoes from Migrating Birds. All photographs were made with the STC circuit off. The date and simultaneous migration traffic rate are below each photograph.



9 May 1977 TR = 2,000

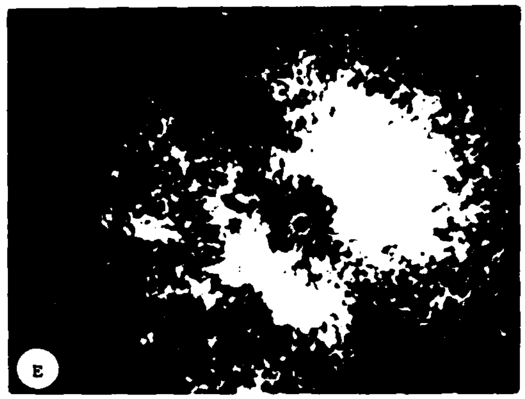


12 May 1977 TR = 5,000

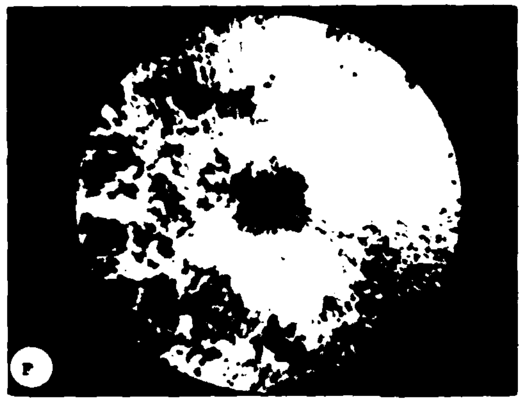


24 April 1977 TR = 10,400

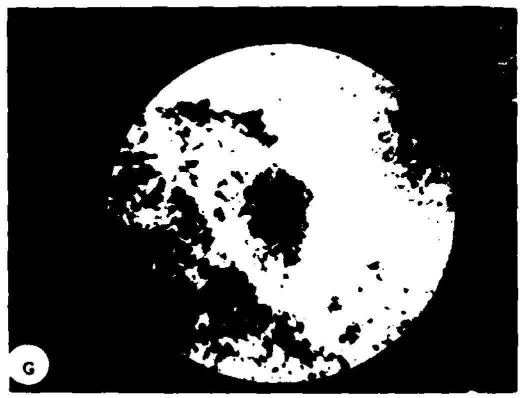
21 April 1977 TR = 12,000



28 April 1977 TR = 21,600



11 May 1977 TR = 32,400



26 September 1977 TR = 52,000

28 September 1977 TR = 218,700

(Figure 8B). The wedge is always oriented perpendicular to the direction of echo movement and is the result of birds being eliminated at the point where their flight paths are tangential to the sweep of the beam. In Figure 8B the wedge is between the azimuths of 60° and 240°.

Figure 9 shows flocks of shorebirds moving early in the evening before the echoes from smaller songbirds increase in number on the PPI. Figure 9 shows the PPI of the ASR-4 when isolated flocks of ducks containing 8 - 10 individuals are migrating. The larger echoes from ducks and shorebirds move at greater speeds (air speeds 30 - 45 knots [55 - 83 kph]) than do songbirds (15 - 25 knots [28 - 46 kph]), and the larger echoes often appear on the radar screen near the time of sunset when there is still enough twilight to see ground objects distinctly. Shortly after dark even though flocks of ducks and shorebirds are still on the PPI, they are largely obscured by the numerous echoes from the smaller songbirds. On the average, the larger, faster flying birds that produce larger dot echoes fly higher than do the smaller, slower flying birds that produce the numerous small dot echoes (see subsequent section on altitude).

The procedure followed to quantify the displays of bird echoes on the ASR-4 is straightforward, and is based on the direct comparison of moon-watch traffic rates (MTR) or ceilometer traffic rates (CTR) and the density of echoes on the radar screen at the same time. Once portions of the display are saturated with bird echoes, the CSS circuits can be engaged, and the density of echoes on the PPI is reduced because of the reduction in receiver sensitivity. Figure 12 shows the radar screen of the ASR-4 on 6 naut.m (11 km) range almost completely saturated with bird echoes; the MTI wedge is between 320° and 140°. Figure 12B, in contrast, shows the result of engaging the CSS-1 circuit that lowers the receiver sensitivity by 12 db, reducing the number of bird echoes by a factor of approximately 16.

In 1976 the cross sectional sensitivity (CSS) circuits in the ASR-4 were replaced by additional sensitivity time circuits (STC-2 and STC-3). These circuits along with the STC-1 were standardized with reference to a fixed IF gain setting. Consequently, much of the variability in the IF gain settings and in the STC attenuation curves from radar to radar was eliminated. These modifications permitted the development of a scheme for quantifying the radar displays

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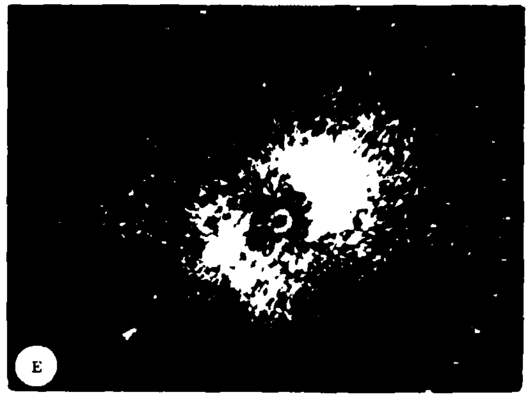
Figure 14. Photographs of the PPI of the ASR-4 on 6 naut.m (11 km) Range Showing Different Densities of Echoes from Migrating Birds. All photographs were made with the STC-1 circuit engaged. The date and simultaneous migration traffic rate are below each photograph.

9 May 1977 TR = 2,000

12 May 1977 TR = 5,000

24 April 1977 TR = 10,400

[illegible]1 April 1977 TR = 12,[illegible]



28 April 1977 TR = 21,600

11 May 1977 TR = 32,400

26 September 1977 TR = 52,000

28 September 1977 TR = 218,700

of bird migration on the ASR-4 that could be used at different ASR-4 stations. By making a series of radar photographs with STC off, STC-1 on, STC-2 on, and STC-3 on, it became possible to compare the density of bird echoes on the radar displays from night to night and in turn to compare these photographs with their corresponding migration traffic rates determined by moon-watching and ceilometer - image intensifier observations. On 14 nights in 1977 it was possible to obtain accurate migration traffic rates to quantify the radar photographs.

Figure 13 shows a series of eight radar photographs of the PPI of the ASR-4 with STC off. Below each photograph is the date and the migration traffic rate recorded near the time the photograph was made. As can be seen, the series of photographs shows increasing amounts of bird echoes until the PPI becomes saturated and it is difficult to evaluate further the density of echoes on the radar screen. This problem is corrected by using the STC-1 circuit. The series of photographs in Figure 14 clearly illustrates the effects of the STC-1 circuit. This circuit differentially reduces receiver sensitivity as a function of range (see Table 6). Consequently, the displays that were saturated with bird echoes with the STC off show far less saturation with the STC-1 engaged. The density patterns can now be clearly differentiated. The migration traffic rates are given below each photograph. Figure 15 shows the influence of the STC-2. On those nights with migration traffic rates below 10,000, the PPI does not show sufficient echoes from birds to warrant a photograph when the STC-2 is engaged. With the STC-3 turned on the radar display will show bird echoes only on those nights with migration traffic rates above 100,000 (Figure 16).

Thus the series of ASR-4 photographs of bird migration on 11.1 km (6 nm) range, once "calibrated" with actual migration traffic rates, can be used to determine the amount of bird migration wherever an ASR-4 radar is located. To obtain maximally accurate migration information from the radar displays alone, calibration should be verified at the beginning of a study to make certain the radar settings are comparable to those used in this study.

During the course of my radar work with the ASR-4 at the Greenville-Spartanburg Airport in 1977, whenever the migration traffic rate was above 30,000, some airline pilots

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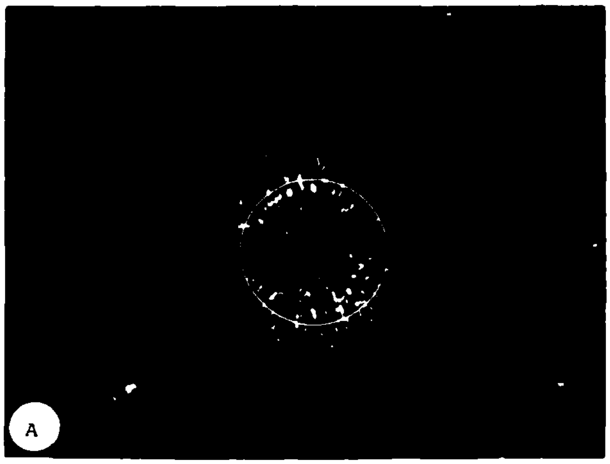
Figure 15. Photographs of the PPI of the ASR-4 on 6 naut.m (11 km) Range Showing Different Densities of Echoes from Migrating Birds. All photographs were made with the STC-2 circuit engaged. The date and simultaneous migration traffic rate are below each photograph.



21 April 1977 TR = 12,000

26 September 1977 TR = 52,000

28 April 1977 TR = 21,600

28 September 1977 TR = 218,700

11 May 19[illegible] TR = 32,4[illegible]

TABLE 6

ATTENUATION LEVELS AT VARIOUS RANGES

FOR SENSITIVITY TIME CONTROL (STC) CIRCUITS

(FAA Radar, ASR-4)

RANGE			STC CIRCUITS		
naut.m	(km)	μsec[1]	STC-1	STC-2	STC-3
20	(37)	250	0	0	0
10	(18)	125	6 db	9 db	12 db
5	(9)	62	12 db	18 db	24 db
2.5	(4.5)	31	18 db	27 db	36 db

[1] 12.345 μsec = 1 naut.m; 6.673 μsec = 1 km

reported small bird strikes, and all pilots reported small birds in their landing lights during approach and takeoff. On the evening of 28 September 1977, two bird strikes were reported withing one-half hour near the airport, and numerous small birds were reported to have been seen in the landing lights as jet airliners approached and departed from the airport. On this night approximately 218,000 birds were crossing over a line one statute mile (1.6 km) long per hour, and in five hours more than 1 million birds flew over the immediate airport vicinity.

Flight controllers working with the ASR-4 do not generally use short ranges but work at ranges between 20 and 60 naut.m (37 - 111 km). Figure 17 shows the appearance of the PPI on 20 naut.m (37 km) range with various migration traffic rates. The change in the extent of the display of bird echoes agrees well with different densities of birds

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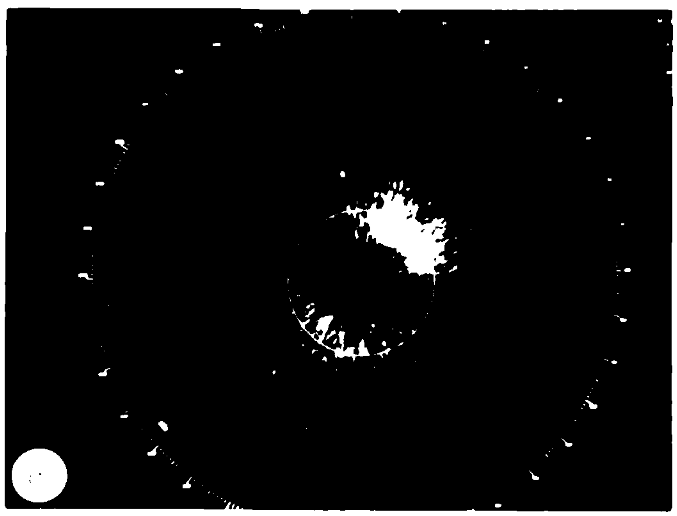
Figure 16. Photographs of the PPI of the ASR-4 on 6 naut.m (11 km) Range Showing Different Densities of Echoes from Migrating Birds. All photographs were made with the STC-3 circuit engaged. The date and simultaneous migration traffic rate are below each photograph.

21 April 1977 TR = 12,000

11 May 1977 TR = 32,400



28 September 1977 TR = 218,700

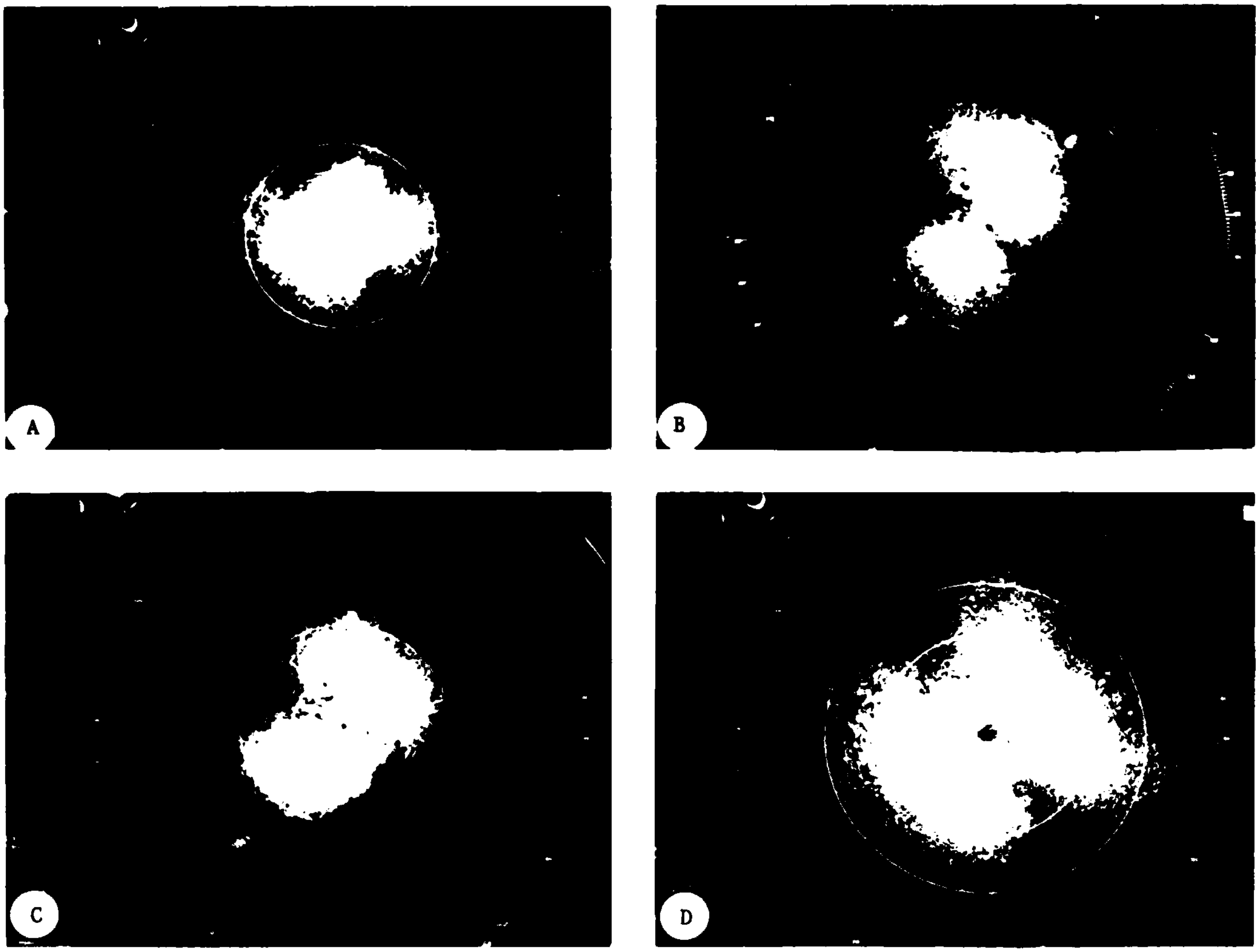


Figure 17. Radar Photographs of the ASR-4 on 20 naut.m (37 km) Range Showing Various Density Patterns Corresponding to Various Migration Traffic Rates as Determined by Direct Visual Observations. MTI and CSS-1 on, IF gain high. (A) 16 May 1973, 20:04 EST, MTR = 3,660. (B) 1 October 1972, 19:40 EST, CTR = 10,764. (C) 13 May 1973, 21:33 EST, MTR = 8,995. (D) 10 May 1973, 20:45 EST, MTR = 17,121.

aloft. It would appear that the greater the number of birds aloft, the greater the range the echo pattern extends outward from the center of the display. Nisbet (1963) has previously discussed this phenomenon.

A word of caution concerning the use of photographs to portray echo densities on radar screens is appropriate at this time. It is true that the brightness of the overall echo display on the PPI is largely dependent on the number of bird echoes, but not exclusively so. Brightness can be enhanced by having the video gain set too high, causing "blooming" of the dot echoes in the photoghraph. The aperture setting of the camera is also important. A camera with the _f_ stop too low (open too much) will also cause the echoes to become radiant and excessively glary. Both of these problems are not serious if one is careful in examining and interpreting the radar photographs. A high video gain problem is readily identifiable, if for example, the echoes appear quite bright and glary, but the azimuth ring is dull and sharp and not "overexposed." An overexposure problem is also easy to diagnose. In this case the radar echoes and the azimuth ring as well as other items in the photograph appear too bright and glary. In evaluating the relative densities of bird echoes on the PPI in a number of photographs it is quite important to keep these matters in mind.

2.5 THE ALTITUDE OF BIRD MIGRATION

The use of radars with range-height indicators (RHI) has greatly aided investigators in their determinations of the altitudes at which birds migrate. Most birds migrate at altitudes of less than a mile above the ground. Smaller songbirds flying singly at night tend to migrate at lower altitudes than do stronger flying waterfowl and shorebirds in flocks. The altitudinal distribution of all migrants aloft is generally skewed to the lower levels with the median usually between 1,000 and 1,500 ft (300 - 450 m) above ground level (Able 1970, Bellrose 1971, Gauthreaux 1972). This pattern can change dramatically when wind conditions become adverse at lower altitudes but are favorable at higher altitudes. On these occasions most birds aloft are found at higher altitudes where the winds are favorable.

Over the water the altitude of migration is usually higher than over land. This is particularly true for the Gulf of Mexico and the Atlantic Ocean southeast of the United States. Gauthreaux (1972) found that along the northern Gulf Coast flocks of songbirds arriving from over the Gulf occurred at altitudes of 4,000 - 5,000 ft (1,200 - 1,500 m), but at nightfall the migrants lowered their altitude approximately 3,000 ft (900 m), and thereafter most were found between 800 - 1,600 ft (240 - 490 m). Hilditch et al. (1973) found the mean altitude of migration over Antigua, West Indies, to be 2,700 m with birds seen as high as 6,500 m. They found few birds below 1,500 m.

2.5.1 WSR-57 RADAR

The WSR-57 radar has a 2° conical beam and a range-height indicator (RHI) which can give the altitudinal distribution of birds aloft. The radar can operate in the RHI mode automatically or manually. Altitudinal information can be derived directly from the PPI when the beam is elevated slightly above the horizontal. Attenuation can be used to determine the relative abundance of birds at various altitudes. Increased attenuation also reduces the beam width providing greater resolution for altitudinal measurements.

Figure 18 shows the RHI of the WSR-57 when birds are migrating during the day over New Orleans after completing a flight across the Gulf of Mexico. One layer of bird echoes is centered between 10,000 - 15,000 ft (3,000 - 4,600 m), and the other is located at 3,000 - 5,000 ft (900 - 1,500 m). The upper layer of bird echoes is produced by flocks of land birds (mostly Passerines), and the lower layer is produced by flocks of shorebirds (Charadriiformes). This situation is unusual because shorebirds usually migrate at higher altitudes than passerines. The cloud conditions at the time Figure 18 was made were 5% cumulus at 3,000 ft (900 m) and scattered cirrus.

A more accurate determination of altitude can be made by elevating the radar beam in 1° increments and attenuating the signal until the solid masses of bird echoes begin to break up. If the measurements are made at a range of 10 naut.m (18 km), the vertical beam width of the WSR-57 is approximately 2,000 ft (600 m), and an accuracy of 1,000 ft (300 m) is theoretically possible. Able (1970) has used this technique quite successfully.

2.5.2 ASR-4 RADAR

Because the ASR-4 has a primary beam of 5° in the vertical it can provide only relatively coarse measurements of the altitude of bird echoes, but nonetheless even this information has value. The vertical beam width is usually defined as the angle between the points at which the radiated energy is 1/2, or 3 db less than, that in the center or axis of the beam. For weak echoes like those from most

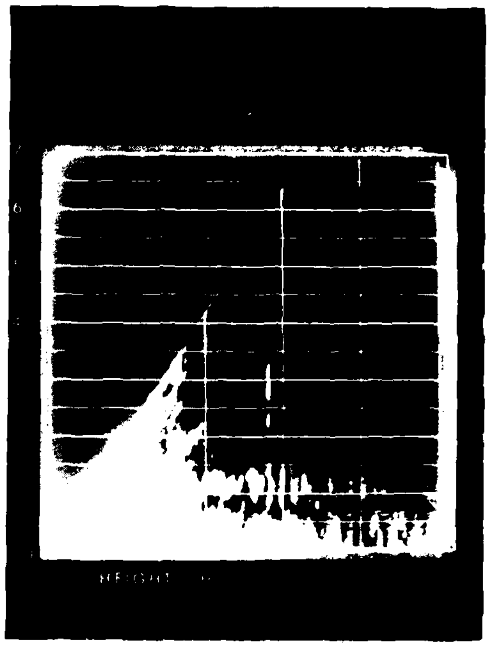


Figure 18. Photograph of the WSR-57 Radar's RHI Showing Daytime Migration over New Orleans, Louisiana, on 8 April 1966 at 18:15 CST. Vertical range marks every 5 naut.m (9 km), 25 naut.m (46 km) range, azimuth 115°. Ground clutter out to 10 naut.m (18 km) and bird echoes between 10,000 and 15,000 ft (3,000 - 4,600 m) and 3,000 and 5,000 ft (900 - 1,500 m).

birds this means that they are probably detected closer to the axis rather than at positions near the "edge" of the radar beam. Thus the effective beam width of the ASR-4 is likely less than 5°. Table 7 gives the altitudinal strata sampled by the ASR-4 at various ranges. With the aid of this table one can readily see that the majority of the higher flying birds in Figure 19B are probably above 3,000 ft (900 m), while most of the lower flying birds are below this altitude. Figure 19 shows a radar display on the ASR-4 when birds at different altitudes are migrating in different directions in favorable wind fields at their respective altitudes. The lower birds (songbirds) are moving toward the ENE on WSW winds, but the migrants at higher altitudes (probably shorebirds) are moving to the SE and SSE on NW and NNW winds. Figure 19A is an exposure for a single revolution of the antenna. Figure 19B is a two minute exposure which emphasizes the movement of the echoes.

TABLE 7

ALTITUDES COVERED BY THE 5° VERTICAL BEAM

OF THE ASR-4 AT VARIOUS RANGES[1]

Range naut.m (km)	Altitude in feet (m) above ground level Base	Axis	Top
2 (3.7)	54 (16)	584 (177)	1118 (338)
4 (7.4)	107 (32)	1167 (353)	2235 (676)
6 (11)	161 (49)	1751 (530)	3353 (1014)
8 (15)	214 (65)	2335 (706)	4470 (1352)
10 (18)	268 (81)	2918 (883)	5586 (1690)
15 (28)	401 (121)	4378 (1324)	8381 (2535)
20 (37)	535 (162)	5837 (1766)	11175 (3380)
30 (56)	803 (243)	8755 (2648)	16763 (5075)

[1] corrected for earth curvature and standard atmospheric refraction. Beam axis elevated 2.75°.

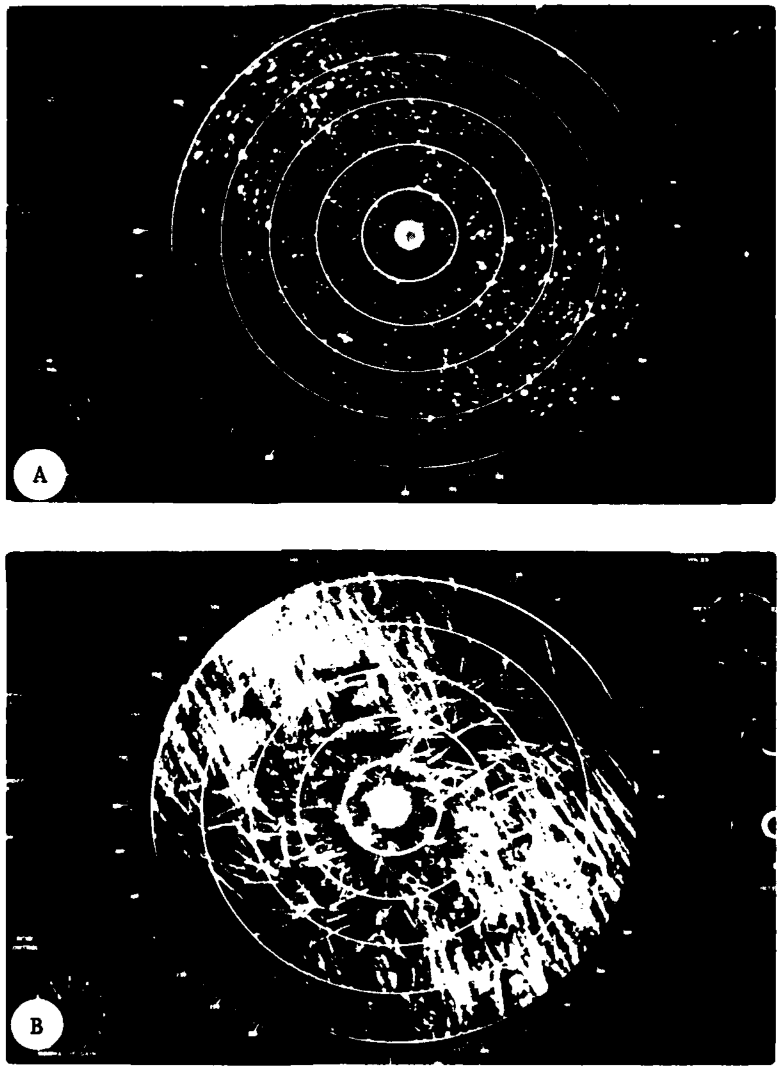


Figure 19. Radar Photographs of the ASR-4 at Greenville, South Carolina, Showing Two Distinct Altitudinal Strata of Birds in Different Wind Fields. MTI on and 10 naut.m (18 km) range. (A) 20 November 1971, 19:46 EST. (B) 20 November 1971, 19:47 - 19:49 EST.

2.6 THE TIMING OF BIRD MIGRATION

The subject of the timing of bird migration is most usefully considered in two separate categories:

1. the seasonal timing of migration, and

2. the daily timing of migratory activity.

With regard to the seasonal timing, the species involved and the geographical locality are important factors. Migration in the United States occurs in the spring and the fall. Winter movements of large numbers of birds occur rarely and are usually associated with intense winter storms that cover feeding areas with deep snow and freeze open water. An overview of the subject of bird migration can be found in Dorst (1962), Gauthreaux (1978), and Griffin (1974).

2.6.1 THE SEASONAL TIMING

Spring migration starts in late February and early March in the states along the Gulf of Mexico. Waterfowl and shorebirds are the first to move northward. Geese generally depart from the Gulf coastal states in mid-March. Swarms of small songbirds overwintering in the tropics also begin to arrive in the southern United States in March. By mid-April most waterfowl are moving northward through the United States, and tremendous numbers of small songbirds are making their way to northern forests. By the middle of May most bird migration is over for the southern states, but at more northern localities, the procession of migrants is still in full swing. Not until the middle of June is there a dramatic decrease in the numbers of migrants aloft; most are then breeding and raising young.

The return south in fall starts as soon as the adult birds have raised their young. By July many species of shorebirds are already making their way south. Usually the first cold fronts in August for the northern states and in September for the southern states trigger massive southward migrations of songbirds. By late October many songbirds have left the United States and are arriving on their wintering grounds in the tropics, or they have settled in the southern states. It is at this time that the heavy waterfowl flights begin. These continue into November as cold fronts become stronger and freezes more frequent. By the end of November most fall migration is over, and except for periods of severe winter storms the birds show little migratory activity until the end of February or early March.

2.6.2 THE DAILY TIMING

Although one often sees flocks of geese and ducks migrating overhead during the daylight hours, it is perhaps surprising that in fact more birds migrate under the cover of darkness. In general, waterfowl and shorebirds are conspicuous daytime migrants, but these birds migrate just as frequently at night. Blackbirds and certain other songbirds migrate during the day, but most of the smaller songbirds usually migrate at night, and can often be heard giving weak call notes on cloudy or overcast nights. Thus it is not surprising that the greatest problem posed by migrating birds to aircraft occurs at night when the birds cannot be seen unless detected by aircraft landing lights or surveillance radars.

Typically over most of the United States bird migration begins around the time of sunset. The first echoes to appear on the radar screen are usually from flocks of waterfowl and shorebirds. These birds start their movement while there is still sufficient light to see ground objects clearly. About 30 - 45 minutes after sunset, between the time of civil and nautical twilight, the smaller birds initiate their movement. It is at this time that the radar screens of surveillance radars start to become cluttered with numerous small dot or point echoes expanding out from the center of the display. Within 20 - 30 minutes the density of these small echoes increases dramatically, and on nights when moderately sized migrations are underway, the PPI is usually cluttered with bird echoes out to ranges of 10 - 20 naut.m (18 - 37 km). On nights with heavy migrations the number of bird echoes may so clutter the PPI as to make it difficult to track nearby aircraft lacking transponders. Nocturnal migration usually starts to decrease in intensity after midnight, and by dawn most of the birds have landed, and the radar screen is once more uncluttered. Only rarely over most of the United States are daytime migrations of birds so dense that they become conspicuous on the PPI of surveillance radars. On such occasions the birds are usually flocked and produce obvious dot echoes. Along the northern coast of the Gulf of Mexico a unique situation exists during the spring from mid-March to mid-May. Here birds that normally would migrate at night are forced to continue their migration in daylight because of the length of the Gulf crossing. Thus the typical daily migration pattern of songbirds along the northern Gulf Coast in spring is

1. the daytime arrival of flocks of songbirds from over the Gulf,

2. the landing of the migrants in the first extensive inland woodlands, and

3. the resumption of their northward migration, flying singly in the night sky, shortly after dark (Gauthreaux 1971).

Chapter 3

THE INFLUENCE OF WEATHER VARIABLES ON THE DENSITY OF NOCTURNAL MIGRATION IN SPRING

3.1 INTRODUCTION

Until the availability of radars that could detect birds migrating aloft at night, studies emphasizing the influence of meteorological variables on the density of nocturnal bird migration suffered because the techniques of study were either indirect (e.g., counting grounded migrants) or limited by certain weather variables (e.g., obscuring clouds in the case of moon-watching). Lack (1960a) reviewed more than 100 papers published between 1880 and 1958 that discussed the influence of weather variables on passerine migration, and he criticized all previous conclusions because most authors had used subjective judgment or univariate statistics to study a multivariate problem. Lack also concluded that radar provided the most adequate measurements of the density of bird migration. At least 12 papers emphasizing the influences of weather variables on bird migration have been published since Lack's review in 1960, and each is based on radar data and employs multivariate statistics. Four of these studies concern only spring migration (Lack 1960b; Nisbet and Drury 1968; Richardson 1971, 1974a); four concern only fall migration (Lack 1963a, Gruys-Casimir 1965, Able 1973, Richardson 1976); and four studies concern both spring and fall migration (Lack 1963b, Geil et al. 1974, Richardson 1974b, Alerstam 1976). An exhaustive recent review of the timing and amount of bird migration in relation to weather has been provided by Richardson (1978).

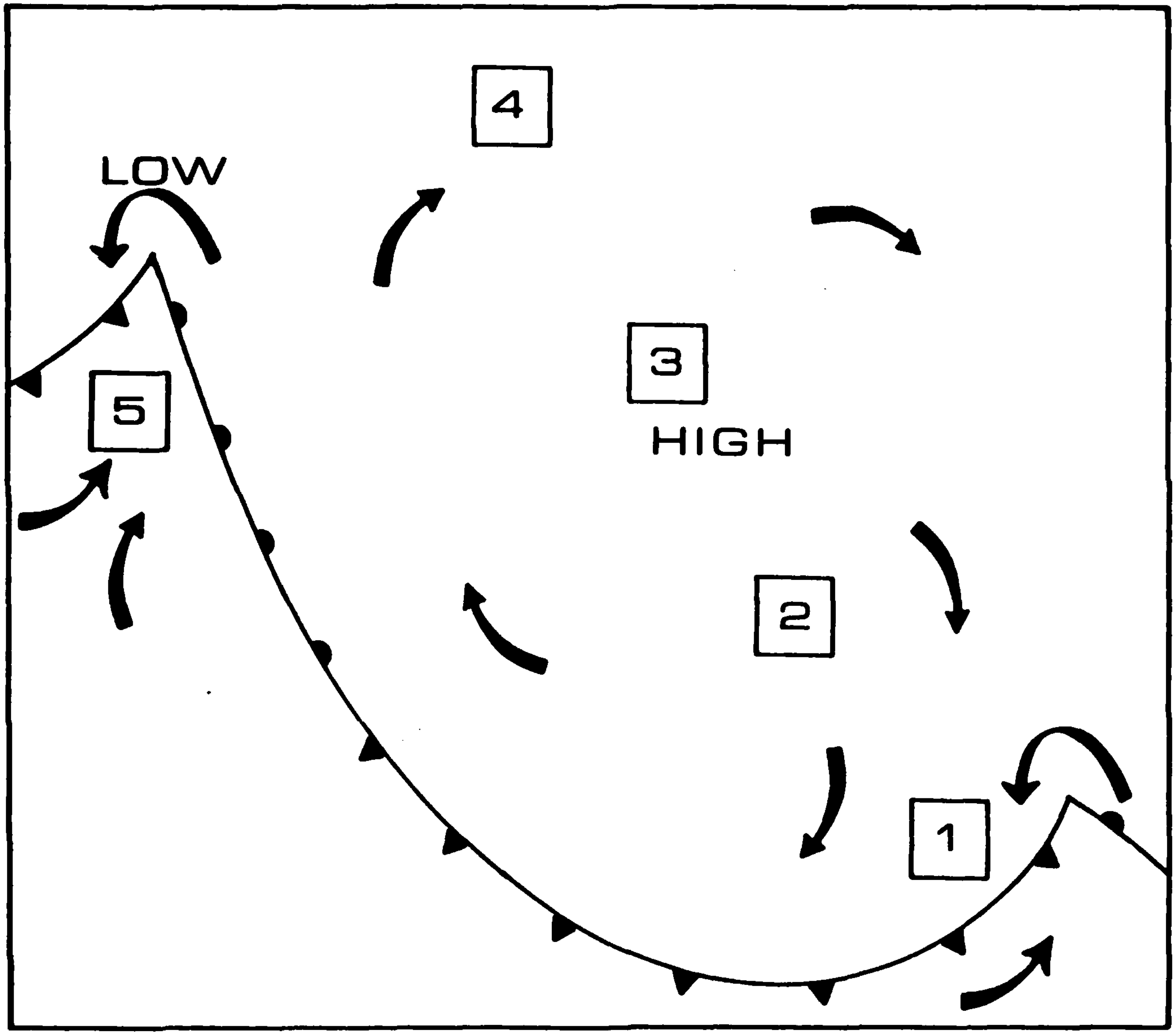
In this chapter I analyze the influence of weather variables on the nocturnal migration of passerine birds in spring using multivariate statistics and review the conclusions of similar studies. The implications of the findings are discussed in terms of the relative contributions of exogenous and endogenous factors to the migratory behavior of birds.

3.2 METHODS

I used the WSR-57 radar at the National Weather Service station at Athens, Georgia, during the spring of 1969 to gather data on the density of nocturnal passerine migration. The peak amount of migration on each of 54 nights sampled from 15 March to 19 May was determined by the techniques discussed in Chapter 2. This method yields density measurements of bird migration detected by the radar that are highly correlated with those obtained by moon-watching (Lowery 1951), and the amount of migration can be expressed as the number of birds crossing a mile of front (1.6 km) per hour, the migration traffic rate.

In the multivariate statistical analyses that follow the maximum density of nocturnal migration on a given night (TR) is the dependent variable. The independent variables are photoperiod (PP), surface wind direction (SWIND), surface wind velocity (SVEL), aloft wind direction at 1,000 ft (300 m; AWIND), aloft wind velocity (AVEL), precipitation during previous daylight hours (PPT), percentage cloud cover (CLDS), cloud height (CLHT), dry bulb temperature (DTEMP), wet bulb temperature (WTEMP), relative humidity (RH), 24-hour change in dry bulb temperature (DLDTMP), 24-hour change in wet bulb temperature (DLWTMP), 24-hour change in relative humidity (DLRH), barometric pressure (BP), 24-hour change in barometric pressure (DLBP), general synoptic weather over station (GENW), precipitation during sample evening (NPPT), and magnetic storm activity (K). In all, 19 independent variables are included in the analysis. Unless noted, the weather variables are those recorded at the beginning of the sample evening (19:00 EST) at the Athens, Georgia, weather station. Any variable reflecting 24-hour change is the difference between the value of the variable at 19:00 EST on the sample evening and the value at 19:00 EST on the previous evening. The value assigned to the general synoptic weather pattern over the station was based on the comparison between the national weather map and Figure 20. Wind direction is a circular variable and was linearized before analysis by assigning the value of zero to north winds and the value of 180 to south winds. For winds from the intermediate directions either westerly or easterly the values ranged from 1-179 (e.g., northeast and northwest winds had a value of 45, east and west winds had a value of 90, and so forth). The dependent variable (TR) originally showed a right-skewed and leptokurtic (clumped)

Figure 20. Synoptic Weather Chart Used to Assign Values to the Variable General Weather (GENW). The value (in square box) given to GENW was that most closely associated with the synoptic weather pattern over the study site based on examination of the actual surface weather map for 19:00 EST.


LOW
4
3
HIGH
5
2
1

distribution, and was normalized by a square-root transformation. Other details of this analysis follow the recommendations of Richardson (1974b).

The statistical analyses of the data included multiple correlation (CORR), stepwise regression (STEPWISE), and maximum R (MAXR) procedures in SAS (Statistical Analysis System; Barr and Goodnight 1972); and stepwise multiple discriminant analysis using the BMD07M program (Dixon 1973). For stepwise multiple discriminant analyses the dependent variable (TR) was divided first into two categories, no migration vs. migration, and subsequently into three categories, zero, light, and heavy migration.

3.3 RESULTS AND DISCUSSION

Multiple correlation analysis showed that the nightly intensity of migration was correlated positively with dry bulb temperature ($p<0.0001$), general synoptic weather ($p<0.0003$), surface wind direction ($p<0.0004$), 24-hour change in dry bulb temperature ($p<0.0006$), aloft wind direction ($p<0.0007$), wet bulb temperature ($p<0.0009$), and 24-hour change in wet bulb temperature ($p<0.0036$). Migration traffic rate was correlated negatively with aloft wind velocity ($p<0.0060$), and surface wind velocity ($p<0.0067$). Associations of traffic rate with the remaining variables were not significant at the 0.05 probability level.

In an effort to examine the makeup of the variable general synoptic weather, GENW, a maximum R procedure was performed with GENW as the dependent variable and with migration density (TR) excluded. With all the weather variables included, only 73% of the variance in general synoptic weather was explained. It thus appears that general synoptic weather includes additional weather parameters not specified by the array of weather variables I have chosen for my analysis. In addition, a stepwise regression analysis was performed to examine the most important weather variables that contributed to the dependent variable GENW. The resulting model contained only three variables: the direction of aloft wind, the velocity of aloft wind, and the 24-hour change in wet bulb temperature. These three variables accounted for 48% of the variance in synoptic weather, and the aloft wind direction alone accounted for 41% of the variance in GENW.

Stepwise regression analysis generated the best predictive model for migration traffic rate with only four variables -- dry bulb temperature, general synoptic weather, precipitation during the sample night, and velocity of aloft winds at 1,000 ft (305 m) -- explaining 54% of the variance in migration intensity (Table 8).

TABLE 8

STEPWISE REGRESSION ANALYSIS FOR SPRING MIGRATION

Number in Model	R-Square	Variables in Model[1]
1	0.38	DTEMP
2	0.44	DTEMP GENW
3	0.49	DTEMP NPPT GENW
4	0.54	AVEL DTEMP NPPT GENW
5	0.55	AVEL DTEMP DLDTMP NPPT GENW
4	0.54	AVEL DTEMP NPPT GENW

[1] The variables in the above models are all significant at the 0.05 probability level for entry into the models.

The model shows the following relationship between peak nightly migration density (TR) and the four weather variables:

$$TR = (-66.29 + 1.49 \times DTEMP + 9.13 \times GENW - 28.70 \times NPPT - 0.95 \times AVEL)^2 - 1$$

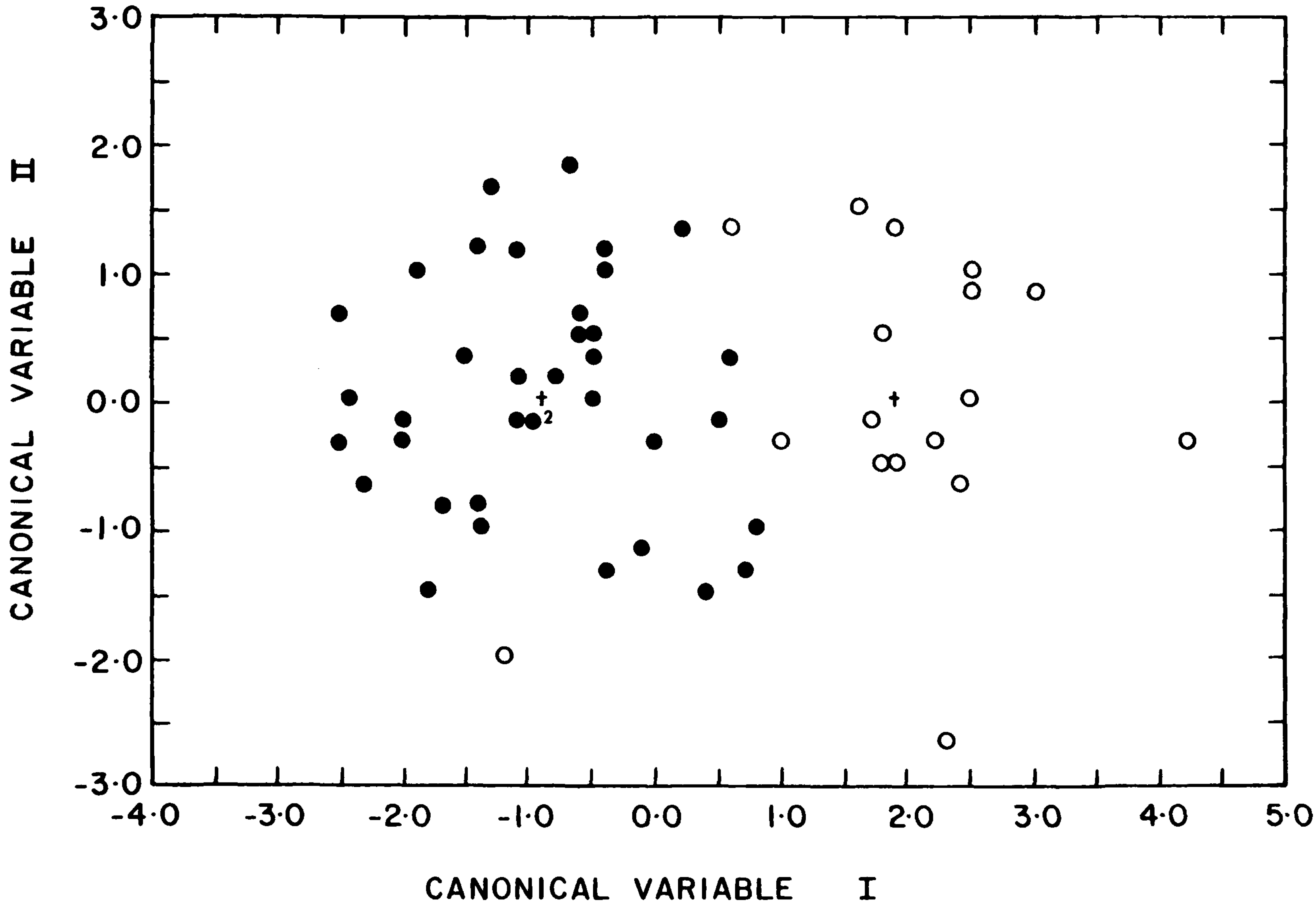
The included weather variables are significant at the 0.05 probability level. One variable alone, dry bulb temperature, explains nearly 40% of the variance in TR. When synoptic weather was eliminated as an independent variable, the best regression model contained only two weather variables, surface wind direction and dry bulb temperature, and explained 44% of the variation in nightly migration traffic rate.

In the first stepwise discriminant function analysis, I attempted to find the weather variables that were most important in discriminating between nights with migration and nights without migration. Based on this analysis, the following variables contributed significantly ($p<0.05$) to the discriminant model: dry bulb temperature, velocity of aloft winds, precipitation during the sample night, and general synoptic weather. Based on this discriminant model, only two of 17 nights without migration were classified incorrectly (88% accuracy), and four of 37 nights with migration were misclassified (89% accuracy). When all 19 weather variables were included in the discriminant analysis the misclassification in the migration category was reduced by only one case (92% accuracy). Thus four weather variables had essentially the same predictive power as the entire set of 19 variables.

When each case of no migration and migration is plotted using the first and second canonical variables, the separation of the two categories of migration traffic rate is clearly evident (Figure 21). The canonical variables incorporate the most important weather variables that allow maximum discrimination between the two categories of migration. The canonical correlation coefficient (Rc) is 0.80, and the proportion of the variance in the discriminant function accounted for by the two groups is 64%.

In the second stepwise discriminant function analysis I divided the dependent variable TR into three categories: zero migration, light migration (traffic rates between 1 and 4500), and heavy migration (traffic rates above 4500). Only three variables were significant ($p<0.05$): dry bulb temperature, general synoptic weather, and relative humidity. On the basis of this discriminant model with these three variables, three of the 17 cases of no migration were misclassified (82% accuracy), 13 of the 28 cases with light migration densities were misclassified (54% accuracy), and two of the nine cases with heavy migration were misclassified (78% accuracy). When all 19 weather variables were included, only one case was misclassified in the zero migration category (94% accuracy), eight of the 28 cases in the light migration category were misclassified (72% accuracy), and none were misclassified in the heavy migration category (100% accuracy). Figure 22 shows the plot of the cases in the three categories along the axes of the first and second canonical variables. As expected, the light migration cases were the most poorly classified, probably because the limits of the category were somewhat arbitrarily defined. The canonical correlation coefficient (Rc) is 0.82 for the first canonical variable and 0.54 for the second canonical variable, and the proportion of the variance in the discriminant function accounted for by the three groups is 67%.

Figure 21. Discrimination Between Nights with No Migration and Nights with Migration on the Basis of Weather. Nights are plotted in relation to the first and second canonical variables. Open circles are cases of no migration and solid circles are cases with migration. "+" indicates group centroids, and points marked "2" are superimposed.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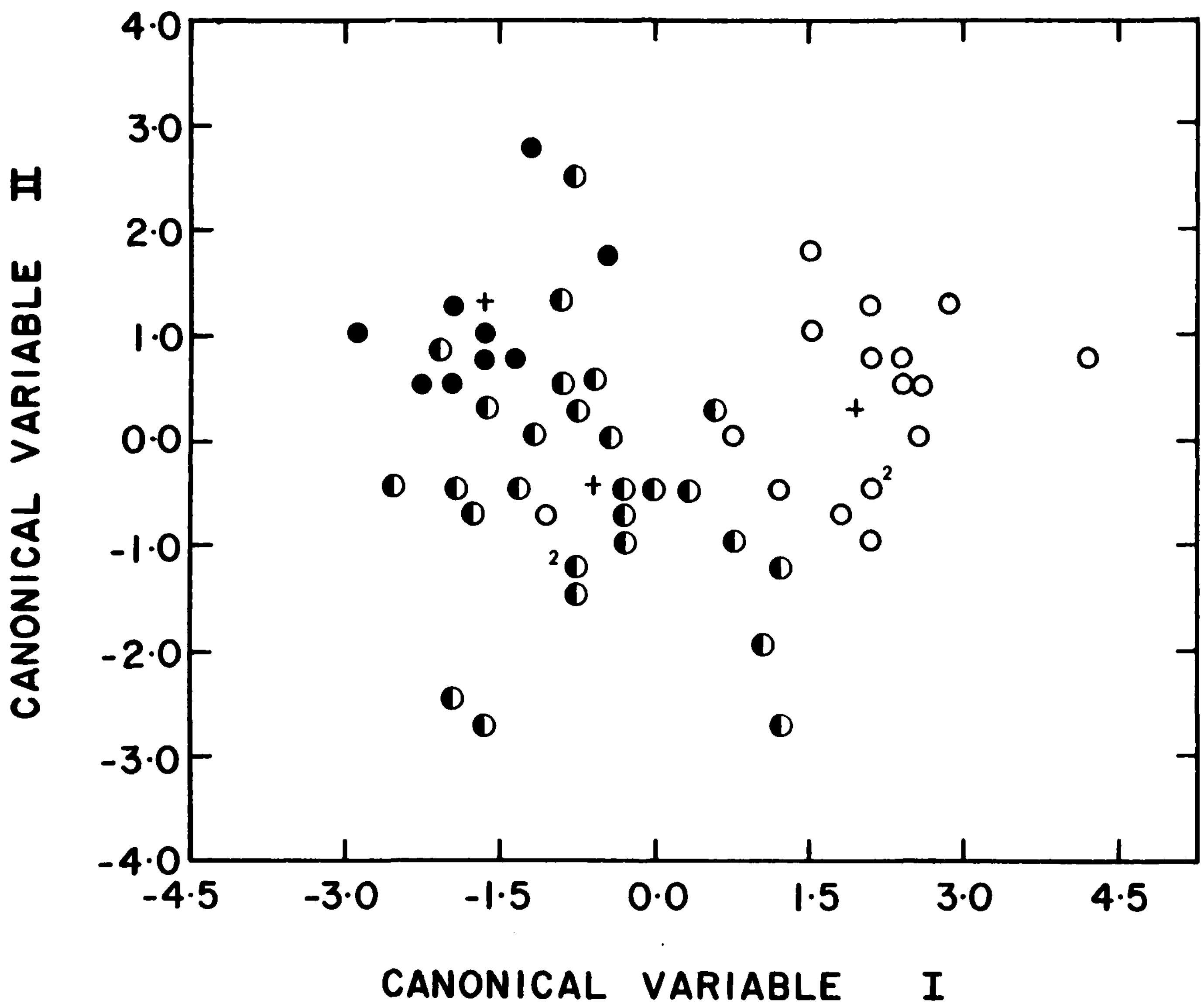
4·0
5·0
2
CANONICAL VARIABLE II
CANONICAL VARIABLE I

Two patterns emerge from all the multivariate studies of weather influence on bird migration. First, of the weather variables that have been shown to have a significant influence on the night-to-night variation in the amount of migration, two variables, temperature and wind, have rather consistently appeared. Aspects of the weather variable wind have been shown to be significant in every study. In my study both wind direction and dry bulb temperature were significantly cross-correlated (partial correlation coefficient 0.43, $p<0.0016$ for direction of surface wind; partial correlation coefficient 0.59, $p<0.0001$ for direction of aloft wind). When one considers the flight energetics of bird migration the importance of both temperature and wind is self-evident. The other pattern evident from multivariate studies of weather and bird migration concerns the percentage of night-to-night variability in the amount of migration explained by the array of weather variables. In spring (Table 9) the average percentage of explained variability is 52% with a range from 40-62%. In the fall (Table 10) the average explained variability is 47% with a range from 26-61%. Thus weather conditions appear to be able to account for only about half of the variation in the amount of nightly migration. The remaining variability is probably dependent on the number of grounded migrants in the general area and on the internal conditions of these migrants relative to their readiness to migrate. However, if we recall that only 70% of the variability in general synoptic weather was accounted for by various weather elements, then it may be futile at the present time to expect to account for more than 70% of night-to-night variance in migration intensity, even with knowledge of the number and condition of potential migrants on the ground.

Figure 22. Discrimination Between Nights with Zero, Light, or Heavy Migration on the Basis of Weather. Nights are plotted in relation to the first and second canonical variables. Open circles are cases of no migration, half-shaded circles are cases of light migration, and solid circles are cases of heavy migration. "+" indicates group centroids, and points marked "2" are superimposed.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3·0
4·5
CANONICAL VARIABLE II
CANONICAL VARIABLE I

TABLE 9

INFLUENCE OF WEATHER VARIABLES ON SPRING MIGRATION

(MULTIVARIATE ANALYSES)

	General Weather Variables[1]							
	Temp	Wind	Cloud	Rel Hum	Bar Press	Precip	Gen Weath	R^2 or Rc^2
Lack (1960b)	*	*	*			*		
Lack (1963b)	*	*	*				*	
Nisbet & Drury (1968)	*	*		*	*	*		0.60
Richardson (1971, 1974b)	*	*	*					0.62
Geil et al. (1974)[2]	*	*		*	*			0.61
Geil et al. (1974)[3]	*	*	*			*		0.43
Richardson (1974a)[4]		*			*			0.51
Richardson (1974a)[5]		*						0.40
Alerstam (1976)		*		*	*		*	0.44
Gauthreaux (1976)	*	*				*	*	0.54

[1] Specific weather variables (e.g., 24-hour change in temperature, temperature departure from normal) are included in general variable (e.g., temperature). [2] March. [3] April. [4] offshore. [5] overland.

TABLE 10

INFLUENCE OF WEATHER VARIABLES ON FALL MIGRATION

(MULTIVARIATE ANALYSES)

	General Weather Variables[1]									
	Temp	Wind	Cloud	Visibil	Rel Hum	Bar Press	Precip	Gen Weath	Mag Dist	R^2 or Rc^2
Lack (1960a)		*								
Lack (1963a)[3]	*	*	*					*		
Able (1973)	*	*						*		0.54
Geil et al. (1974)[2]	*	*				*				0.44
Geil et al. (1974)[4]	*			*	*					0.48
Richardson (1974b)	*	*			*	*	*			0.51
Alerstam (1976)	*	*	*	*	*	*		*		0.61
Bruderer (1977)		*				*				0.52

1 Specific weather variables (e.g., 24-hour change in temperature, temperature departure from normal) are included in general variable (e.g., temperature). 2 September. 3 October-November. 4 November.

3.4 SUMMARY

Fifty-four nights of radar data were gathered and processed according to the methods of Chapter 2 yielding accurate estimates of migration traffic rates. The highest hourly migration traffic rate for each night (the dependent variable) was analyzed in terms of 19 weather parameters (independent variables) gathered at the beginning of each night by several statistical procedures: simple correlation, stepwise regression, and discriminant analysis. When necessary the data were transformed as recommended by Richardson (1974b).

Nine weather variables were found to be significantly correlated with migration traffic rate. Dry bulb temperature accounted for 37% of the variation in migration traffic rate; the best multiple regression model included four variables -- aloft wind velocity, dry bulb temperature, synoptic weather, and nightly precipitation -- and explained 54% of the variation in nightly migration traffic rate. When synoptic weather was eliminated the best regression model contained only two variables, surface wind direction and dry bulb temperature, and explained 44% of the variation in nightly migration traffic rate.

The stepwise discriminant function analyses showed that dry bulb temperature, velocity of winds aloft, precipitation during the sample night, and general synoptic weather contributed most significantly to the discriminant model for predicting migration vs. no migration. The discriminant model for separating the categories no migration, medium migration, and heavy migration relied strongly on just three variables: dry bulb temperature, general synoptic weather, and relative humidity.

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